Exhibit 73

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QUINN EMANUEL URQUHART & SULLIVAN, LLP
Charles K. Verhoeven (Bar No. 170151)
charlesverhoeven@quinnemanuel.com
David A. Perlson (Bar No. 209502)
davidperlson@quinnemanuel.com
Melissa Baily (Bar No. 237649)
melissabaily@quinnemanuel.com
John Neukom (Bar No. 275887)
johnneukom@quinnemanuel.com
Jordan Jaffe (Bar No. 254886)
jordanjaffe@quinnemanuel.com
50 California Street, 22nd Floor
San Francisco, California 94111-4788
Telephone: (415) 875-6600
Facsimile: (415) 875-6700

Attorneys for WAYMO LLC

UNITED STATES DISTRICT COURT

NORTHERN DISTRICT OF CALIFORNIA, SAN FRANCISCO DIVISION

WAYMO LLC, Plaintiff, vs. UBER TECHNOLOGIES, INC.; OTTOMOTTO LLC; OTTO TRUCKING LLC, Defendants.	CASE NO. ____________ **COMPLAINT** **1. VIOLATION OF DEFENSE OF TRADE SECRETS ACT** **2. VIOLATION OF CALIFORNIA UNIFORM TRADE SECRET ACT** **3. PATENT INFRINGEMENT** **4. VIOLATION OF CAL. BUS & PROF. CODE SECTION 17200** **DEMAND FOR JURY TRIAL**

Plaintiff Waymo LLC ("Waymo"), by and through their attorneys, and for their Complaint against Uber Technologies, Inc. ("Uber"), Ottomotto LLC, and Otto Trucking LLC (together, "Otto") (collectively, "Defendants"), hereby allege as follows:

I. INTRODUCTION

1. This is an action for trade secret misappropriation, patent infringement, and unfair competition relating to Waymo's self-driving car technology. Waymo strongly believes in the benefits of fair competition, particularly in a nascent field such as self-driving vehicles. Self-driving cars have the potential to transform mobility for millions of people as well as become a trillion dollar industry. Fair competition spurs new technical innovation, but what has happened here is not fair competition. Instead, Otto and Uber have taken Waymo's intellectual property so that they could avoid incurring the risk, time, and expense of independently developing their own technology. Ultimately, this calculated theft reportedly netted Otto employees over half a billion dollars and allowed Uber to revive a stalled program, all at Waymo's expense.

2. Waymo developed its own combination of unique laser systems to provide critical information for the operation of fully self-driving vehicles. Waymo experimented with, and ultimately developed, a number of different cost-effective and high-performing laser sensors known as LiDAR. LiDAR is a laser-based scanning and mapping technology that uses the reflection of laser beams off objects to create a real-time 3D image of the world. When mounted on a vehicle and connected to appropriate software, Waymo's LiDAR sensors enable a vehicle to "see" its surroundings and thereby allow a self-driving vehicle to detect traffic, pedestrians, bicyclists, and any other obstacles a vehicle must be able to see to drive safely. With a 360-degree field of vision, and the ability to see in pitch black, Waymo's LiDAR sensors can actually detect potential hazards that human drivers would miss. With a goal of bringing self-driving cars to the mass market, Waymo has invested tens of millions of dollars and tens of thousands of hours of engineering time to custom-build the most advanced and cost-effective LiDAR sensors in the industry. Thanks in part to this highly advanced LiDAR technology, Waymo became the first company to complete a fully self-driving trip on public roads in a vehicle without a steering wheel

and foot pedals. Today, Waymo remains the industry's leader in self-driving hardware and software.

3. Waymo was recently – and apparently inadvertently – copied on an email from one of its LiDAR component vendors. The email attached machine drawings of what purports to be an Uber LiDAR circuit board. This circuit board bears a striking resemblance to Waymo's own highly confidential and proprietary design and reflects Waymo trade secrets. As this email shows, Otto and Uber are currently building and deploying (or intending to deploy) LiDAR systems (or system components) using Waymo's trade secret designs. This email also shows that Otto and Uber's LiDAR systems infringe multiple LiDAR technology patents awarded to Waymo.

4. Waymo has uncovered evidence that Anthony Levandowski, a former manager in Waymo's self-driving car project – now leading the same effort for Uber – downloaded more than 14,000 highly confidential and proprietary files shortly before his resignation. The 14,000 files included a wide range of highly confidential files, including Waymo's LiDAR circuit board designs. Mr. Levandowski took extraordinary efforts to raid Waymo's design server and then conceal his activities. In December 2015, Mr. Levandowski specifically searched for and then installed specialized software onto his company-issued laptop in order to access the server that stores these particular files. Once Mr. Levandowski accessed this server, he downloaded the 14,000 files, representing approximately 9.7 GB of highly confidential data. Then he attached an external drive to the laptop for a period of eight hours. He installed a new operating system that would have the effect of reformatting his laptop, attempting to erase any forensic fingerprints that would show what he did with Waymo's valuable LiDAR designs once they had been downloaded to his computer. After Mr. Levandowski wiped this laptop, he only used it for a few minutes, and then inexplicably never used it again.

5. In the months leading to the mass download of files, Mr. Levandowski told colleagues that he had plans to set up a new, self-driving vehicle company. In fact, Mr. Levandowski appears to have taken multiple steps to maximize his profit and set up his own new venture – which eventually became Otto – before leaving Waymo in January 2016. In addition to downloading Waymo's design files and proprietary information, Mr. Levandowski set up a

competing company named "280 Systems" (which later became Otto) before he left, under the pretense that 280 Systems would not compete with Waymo.

6. A number of Waymo employees subsequently also left to join Anthony Levandowski's new business, downloading additional Waymo trade secrets in the days and hours prior to their departure. These secrets included confidential supplier lists, manufacturing details and statements of work with highly technical information, all of which reflected the results of Waymo's months-long, resource-intensive research into suppliers for highly specialized LiDAR sensor components.

7. Otto launched publicly in May 2016, and was quickly acquired by Uber in August 2016 for $680 million. (Notably, Otto announced the acquisition shortly after Mr. Levandowski received his final multi-million dollar compensation payment from Google.) As was widely reported at the time, "one of the keys to this acquisition[] could be the LIDAR system that was developed in-house at Otto."

8. Uber's own attempts to develop self-driving cars started earlier in February 2015 with the announcement of a strategic partnership with Carnegie Mellon University and the creation of the Uber Advanced Technologies Center in Pittsburgh. Reports attribute Uber CEO Travis Kalanick's interest in this technology to a ride in a Google, now Waymo, self-driving car. Uber's CEO has described self-driving cars as "existential" to the survival of his company.[1] He told reporters: "the entity that's in first, then rolls out a ride-sharing network that is far cheaper or far higher-quality than Uber's, then Uber is no longer a thing." However, by March 2016 reports surfaced that the partnership between CMU and Uber had "stalled."

9. Meanwhile, Waymo had devoted seven years to research and development. It had amassed nearly one and a half million miles of self-driving experience on public roads and billions of miles of test data via simulation. By May 2015, Waymo had also designed and built, from the ground up, the world's first fully self-driving car without a steering wheel and foot pedals. These

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[1] Biz Carson, "Travis Kalanick on Uber's bet on self-driving cars: 'I can't be wrong,'" *Business Insider*, Aug. 18, 2016, *available at* http://www.businessinsider.com/travis-kalanick-interview-on-self-driving-cars-future-driver-jobs-2016-8.

vehicles were equipped with Waymo's own in-house hardware and sensors, including its uniquely-designed LiDAR.

10. Instead of developing their own technology in this new space, Defendants stole Waymo's long-term investments and property. While Waymo developed its custom LiDAR systems with sustained effort over many years, Defendants leveraged stolen information to shortcut the process and purportedly build a comparable LiDAR system in only nine months. As of August 2016, Uber had no in-house solution for LiDAR – despite 18 months with their faltering Carnegie Mellon University effort – and they acquired Otto to get it. By September 2016, Uber represented to regulatory authorities in Nevada that it was no longer using an off-the-shelf, or third-party, LiDAR technology, but rather using an "[i]n-house custom built" LiDAR system. The facts outlined above and elaborated further in this complaint show that Uber's LiDAR technology is actually Waymo's LiDAR technology.

11. In light of Defendants' misappropriation and infringement of Waymo's LiDAR technology, Waymo brings this Complaint to prevent any further misuse of its proprietary information, to prevent Defendants from harming Waymo's reputation by misusing its technology, to protect the public's confidence in the safety and reliability of self-driving technology that Waymo has long sought to nurture, and to obtain compensation for its damages and for Defendants' unjust enrichment resulting from their unlawful conduct.

II. PARTIES

12. Plaintiff Waymo LLC is a subsidiary of Alphabet Inc. with its principal place of business located in Mountain View, California 94043. Waymo is a self-driving technology company with a mission to make it safe and easy for people and things to move around. Waymo LLC owns all of the patents, trade secrets, and confidential information infringed or misappropriated by Defendants.

13. Defendant Uber Technologies, Inc. ("Uber") is a Delaware company with its principal place of business at 1455 Market Street, San Francisco, California.

14. Waymo is informed and believes that Defendant Ottomotto LLC (f/k/a 280 Systems Inc.) is a Delaware limited liability company with its principal place of business located at 737 Harrison Street, San Francisco, California.

15. Waymo is informed and believes that Defendant Otto Trucking LLC (f/k/a 280 Systems LLC) is a limited liability company with its principal place of business located at 737 Harrison Street, San Francisco, California.

16. Waymo is informed and believes that Uber acquired Defendants Ottomotto LLC and Otto Trucking LLC in approximately August 2016.

17. Waymo is informed and believes that each Defendant acted in all respects pertinent to this action as the agent of the other Defendant, carried out a joint scheme, business plan or policy in all respects pertinent hereto, and that the acts of each Defendant are legally attributable to each of the other Defendants.

III. JURISDICTION, VENUE & INTRADISTRICT ASSIGNMENT

18. This Court has subject matter jurisdiction over Waymo's claims for patent infringement pursuant to the Federal Patent Act, 35 U.S.C. § 101 *et seq.* and 28 U.S.C. §§ 1331 and 1338(a). This Court has subject matter jurisdiction over Waymo's federal trade secret claim pursuant to 18 U.S.C. §§ 1836-39 *et seq*. and 28 U.S.C. §§ 1331 and 1343. The Court has supplemental jurisdiction over the state law claim alleged in this Complaint pursuant to 28 U.S.C. § 1367.

19. As set forth above, at least one Defendant resides in this judicial district, and all Defendants are residents of the State of California. In addition, a substantial part of the events or omissions giving rise to the claims alleged in this Complaint occurred in this Judicial District. Venue therefore lies in the United States District Court for the Northern District of California pursuant to 28 U.S.C. §§ 1391(b)(1) and (2).

20. A substantial part of the events giving rise to the claims alleged in this Complaint occurred in the City and County of San Francisco. For purposes of intradistrict assignment under Civil Local Rules 3-2(c) and 3-5(b), this Intellectual Property Action will be assigned on a district-wide basis.

IV. FACTUAL ALLEGATIONS

A. Google Pioneers The Self-Driving Car Space

21. Google was the first major U.S. technology firm to recognize the transformative potential and commercial value of vehicle automation, which promises to make transportation safer, cleaner, more efficient, and more widely available.

22. Google initiated its self-driving car project in 2009. Before long, Google's self-driving cars had navigated from the Bay Area to Los Angeles, crossed the Golden Gate Bridge, drove the Pacific Coast Highway, and circled Lake Tahoe, logging over 140,000 miles – a first in robotics research at the time.

23. Google made its self-driving car project public in 2010, with the following announcement: "Larry and Sergey founded Google because they wanted to help solve really big problems using technology. And one of the big problems we're working on today is car safety and efficiency. Our goal is to help prevent traffic accidents, free up people's time and reduce carbon emissions by fundamentally changing car use. So we have developed technology for cars that can drive themselves."

24. In 2014, Google unveiled its own reference vehicle, a two-door fully autonomous car without pedals or a steering wheel. A year later, this prototype made the first ever fully self-driving trip in normal traffic on public roads.

25. In 2016, Google's self-driving car program became Waymo, a stand-alone company operating alongside Google and other technology companies under the umbrella of Alphabet Inc.[2]

26. To date, Waymo's fleet of self-driving vehicles has logged over 2.5 million miles in autonomous mode on public roads. Measured in time, that equates to over 300 years of human driving experience. And in 2016 alone, Waymo's systems logged over a billion miles of simulated driving, a feat made possible by Waymo's in-house simulator and the power of Google's massive data centers.

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[2] Further references to "Waymo" refer to the self-driving car project from its inception in 2009 to the present.

27. Waymo uses the data collected from these real-world and simulated miles to (among other things) constantly improve the safety of its system, including its hardware and sensors. This focus on testing and safety has allowed Waymo's self-driving cars to become increasingly capable and robust, with less need for human intervention. As just one illustration of this, the rate of Waymo's safety-related disengagements has fallen from 0.8 disengagements per thousand miles in 2015 to 0.2 disengagements per thousand miles in 2016, representing a four-fold improvement in Waymo's self-driving technology in just 12 months. Today, Waymo believes its self-driving cars are the safest on the road.

B. Waymo Develops Its Own Proprietary LiDAR System Tailored For Mass-Marketed Self-Driving Cars

28. Self-driving cars must be able to detect and understand the surrounding environment. With respect to this aspect of vehicle automation, LiDAR – or "Light Detection And Ranging" – uses high-frequency, high-power pulsing lasers to measure distances between one or more sensors and external objects.

29. LiDAR hardware built for autonomous vehicles is typically mounted on the exterior of a vehicle and scans the surrounding environment (sometimes in 360 degrees) with an array of lasers. The laser beams reflect off surrounding objects, and data regarding the light that bounces back to designated receivers is recorded. Software analyzes the data in order to create a three-dimensional view of the environment, which is used to identify objects, assess their motion and orientation, predict their behavior, and make driving decisions.

30. LiDAR systems are made up of thousands of individual hardware and software components that can be configured in virtually limitless combinations and designs. LiDAR systems adapted for use in self-driving cars became commercially available in approximately 2007. Today, most firms in the self-driving space purchase LiDAR systems from third-party providers.

31. Waymo, on the other hand, uses ***its own*** LiDAR systems that are carefully tailored – based on Waymo's extensive research and testing – for use in fully autonomous vehicles in which there is no driver intervention required. Waymo's proprietary LiDAR systems improve the

ability of self-driving cars to navigate safely in all environments, including city environments and highly unusual driving scenarios.

32. Moreover, by designing its own LiDAR systems, Waymo has driven down costs, a well-known barrier to commercializing self-driving technology. Waymo's improved LiDAR designs are now less than 10% of the cost that benchmark LiDAR systems were just a few years ago, and Waymo expects that mass production of their technology will make it even more affordable.

33. One way that Waymo pioneered LiDAR systems with improved performance at lower cost was by innovating a design that, in part, uses a single lens – rather than multiple sets of lenses – to both transmit and receive the collection of laser beams used to scan the surrounding environment. This design greatly simplifies the manufacturing process by eliminating the need to painstakingly align pairs of transmit and receive lenses, with even a slight mis-calibration of a lens pair affecting the accuracy of the system. Waymo was awarded a patent on its design in 2014: United States Patent No. 8,836,922 ("the '922 patent") entitled "Devices and Methods for a Rotating LiDAR Platform with a Shared Transmit/Receive Path."

34. Another way that Waymo improved the performance and lowered the cost of LiDAR systems for autonomous vehicles was by simplifying the design of the laser diode firing circuit that is at the heart of any LiDAR system. Waymo invented a design that elegantly simplified the circuit to control the charging and discharging paths of the lasers compared to the more complicated circuit designs otherwise used by the industry. Waymo obtained a patent on this aspect of its LiDAR design in 2016: United States Patent No. 9,368,936 ("the '936 patent") entitled "Laser Diode Firing System."

35. As one more example of how Waymo fundamentally advanced LiDAR systems for use in autonomous vehicles, Waymo developed a simplified design for "pre-collimating" (or making parallel) the light output of each laser diode separately before the beams are combined. The increased compactness of this design increases the resolution of the overall LiDAR system. Waymo was awarded a patent on this aspect of its design in 2015: United States Patent No.

9,086,273 ("the '273 patent") entitled "Microrod Compressions of Laser Beam in Combination with Transmit Lens."

36. While patenting these fundamental advances in LiDAR technology, Waymo also accumulated confidential and proprietary intellectual property that it uses in the implementation and manufacture of its LiDAR designs to optimize performance, maximize safety, and minimize cost. Waymo also created a vast amount of confidential and proprietary intellectual property via its exploration of design concepts that ultimately proved too complex or too expensive for the mass market; Waymo's extensive experience with "dead-end" designs continues to inform the ongoing development of Waymo's LiDAR systems today. The details actually used in Waymo's LiDAR designs as well as the lessons learned from Waymo's years of research and development constitute trade secrets that are highly valuable to Waymo and would be highly valuable to any competitor in the autonomous vehicle space.

37. Waymo's substantial and sustained investment in LiDAR technology over nearly seven years – and the intellectual property that resulted – have made Waymo's current LiDAR technology the most advanced in the industry. It is unparalleled in performance and safety in all driving environments, including in the most challenging city environments. Yet it is more than 90% cheaper than prior benchmark systems, a key driver toward mass market adoption. For these reasons and others, Waymo's LiDAR technology and the intellectual property associated with it are some of Waymo's most valuable assets.

C. Uber Is Late To Enter The Self-Driving Car Market

38. Whereas Waymo began developing its self-driving cars in 2009, on information and belief, Uber's first serious foray into automation was not until six years later when – in February 2015 – Uber announced a partnership with Carnegie Mellon University. According to public reports of the partnership, Uber hired at least 40 CMU faculty members, researchers, and technicians – including the former head of CMU's National Robotics Engineering Center – to help jump-start an Uber vehicle automation program.

39. By early 2016, Uber had hired hundreds of engineers and robotics experts to support the original team from Carnegie Mellon. But the research and development process was

slow.[3] And with respect to LiDAR technology, Uber's program appeared to rely solely on a third-party, off-the-shelf LiDAR system manufactured by Velodyne Inc. (the HDL-64E). On information and belief, Uber's program did not make any significant advances toward designing or manufacturing its own LiDAR technology for improved performance or lower cost.

40. Thus, although Uber came to view its entry into the self-driving car space as an "existential" imperative,[4] as of mid-2016, Uber remained more than five years behind in the race to develop vehicle automation technology suitable for the mass market.

D. Unbeknownst To Waymo, Anthony Levandowski Lays The Foundation For Defendants To Steal Waymo's Intellectual Property Rather Than Compete Fairly In The Autonomous Vehicle Space

41. While Uber's partnership with CMU was floundering, Waymo was continuing to develop its next-generation proprietary LiDAR technology. But, unbeknownst to Waymo at the time, Waymo manager Anthony Levandowski was also secretly preparing to launch a competing vehicle automation venture – a company named "280 Systems," which later would become Otto.

42. By November 2015, an internet domain name for the new venture had been registered. And by January 2016, Mr. Levandowski had confided in some Waymo colleagues that he planned to "replicate" Waymo's technology at a Waymo competitor. As Waymo would later learn, Mr. Levandowski went to great lengths to take what he needed to "replicate" Waymo's technology and then to meet with Uber executives, all while still a Waymo employee.

43. On December 3, 2015, Mr. Levandowski searched for instructions on how to access Waymo's highly confidential design server. This server holds detailed technical information related to Waymo's LiDAR systems, including the blueprints for its key hardware components, and is accessible only on a need-to-know basis.

44. On December 11, 2015, Mr. Levandowski installed special software on his Waymo laptop to access the design server. Mr. Levandowski then download over 14,000 proprietary files

[3] Heather Somerville, "After a year, Carnegie Mellon and Uber research initiative is stalled," *Reuters*, Mar. 21, 2016, *available at* http://www.reuters.com/article/us-uber-tech-research-idUSKCN0WN0WR.

[4] Max Chafkin, "Uber's First Self-Driving Fleet Arrives in Pittsburgh This Month," *Bloomsberg*, Aug. 18, 2016, *available at* http://www.bloomberg.com/news/features/2016-08-18/uber-s-first-self-driving-fleet-arrives-in-pittsburgh-this-month-is06r7on.

from that server. Mr. Levandowski's download included 9.7 GBs of sensitive, secret, and valuable internal Waymo information. 2 GBs of the download related to Waymo's LiDAR technology. Among the downloaded documents were confidential specifications for each version of every generation of Waymo's LiDAR circuit boards.

45. On December 14, 2015, Mr. Levandowski attached a removable media device (an SD Card) to the laptop containing the downloaded files for approximately eight hours.

46. On December 18, 2015, seven days after Mr. Levandowski completed his download of confidential Waymo information and four days after he removed the SD Card, he reformatted the laptop, attempting to erase any evidence of what happened to the downloaded files. After wiping the laptop clean, Mr. Levandowski used the reformatted laptop for a few minutes and then never used it again.

47. Around the same time, Mr. Levandowski used his Waymo credentials and security clearances to download additional confidential Waymo documents to a personal device. These materials included at least five highly sensitive internal presentations containing proprietary technical details regarding the manufacture, assembly, calibration, and testing of Waymo's LiDAR sensors.

48. After downloading all of this confidential information regarding Waymo's LiDAR systems and other technology and while still a Waymo employee, Waymo is informed and believes that Mr. Levandowski attended meetings with high-level executives at Uber's headquarters in San Francisco on January 14, 2016.

49. The next day, January 15, 2016, Mr. Levandowski's venture 280 Systems - which became OttoMotto LLC - was officially formed (though it remained in stealth mode for several months). On January 27, 2016, Mr. Levandowski resigned from Waymo without notice. And on February 1, 2016, Mr. Levandowski's venture Otto Trucking was officially formed (also remaining in stealth mode for several months).

E. Otto Continues To Misappropriate Waymo's Intellectual Property After Its Public Launch With Mr. Levandowski At The Helm

50. Otto publicly launched in May 2016 with the stated goal of developing hardware and software for autonomous vehicles.

51. In July 2016, a Waymo supply chain manager resigned from Waymo and joined Otto. This supply chain manager was one of several Waymo employees who had spent many months vetting a particular vendor that Waymo ultimately engaged to provide manufacturing services for its self-driving car technology. The vendor's identity and its work for Waymo was and is confidential: Waymo and the vendor entered into a confidentiality agreement that precludes either party from disclosing the existence of their business relationship.

52. Approximately a month before the supply chain manager resigned and despite his confidentiality obligations to Waymo, he downloaded from Waymo's secure network Waymo's confidential supply chain information and other confidential manufacturing information, including Statements of Work (or SOWs) for particular components – all of which reflected the results of Waymo's months-long, resource-intensive research into suppliers for highly specialized LiDAR sensor components.

53. Also in July 2016, a certain Waymo hardware engineer resigned. On the same day that he resigned from Waymo, and despite his confidentiality obligations to Waymo, this engineer downloaded from Waymo's secure network three files containing confidential research into various potential hardware vendors for highly specialized LiDAR components and manufacturing services. On information and belief, this hardware engineer left Waymo to join Otto.

54. In the same time period that these former Waymo employees were downloading Waymo's confidential information regarding its manufacturing and hardware vendors and resigned, Otto contacted the most-extensively vetted (and confidential) Waymo vendor and attempted to order manufacturing services for LiDAR components similar to those the vendor provides to Waymo.

F. After Only Six Months Of Official Existence, Otto Is Acquired By Uber For More Than Half A Billion Dollars

55. In August 2016, shortly after Mr. Levandowski received his final multi-million dollar payment from Google, Uber announced a deal to acquire Otto. Otto's purchase price was reported as $680 million, a remarkable sum for a company with few assets and no marketable product. As *Forbes* reported at the time, "one of the keys to this acquisition[] could be the LIDAR system that was developed in-house at Otto."[5]

56. In recognition of the central role of Otto's technology within Uber, Uber named Otto co-founder Mr. Levandowski as its vice president in charge of Uber's self-driving car project. Uber rechristened Otto's existing San Francisco office as Uber's new self-driving research and development center.

G. Waymo Verifies Its Growing Suspicion That Otto And Uber Stole Its Intellectual Property

57. The sudden resignations from Waymo, Otto's quick public launch with Mr. Levandowski at the helm, and Uber's near-immediate acquisition of Otto for more than half a billion dollars all caused Waymo grave concern regarding the possible misuse of its intellectual property. Accordingly, in the summer of 2016, Waymo investigated the events surrounding the departure of Waymo employees for Otto and ultimately discovered Mr. Levandowski's 14,000-document download, his efforts to hide the disposition of those documents, and the downloading of other Waymo confidential materials by Mr. Levandowski and other former Waymo employees.

58. Then, in December 2016, Waymo received evidence suggesting that Otto and Uber were actually using Waymo's trade secrets and patented LiDAR designs. On December 13, Waymo received an email from one of its LiDAR-component vendors. The email, which a Waymo employee was copied on, was titled OTTO FILES and its recipients included an email alias indicating that the thread was a discussion among members of the vendor's "Uber" team. Attached to the email was a machine drawing of what purported to be an Otto circuit board (the

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[5] Sarwant Singh, "Uber Acquiring Otto Could Be the Lead Domino: Autonomous Vehicles to Spur M&A Activity," *Forbes*, Aug. 24, 2016, *available at* http://www.forbes.com/sites/sarwantsingh/2016/08/24/uber-acquiring-otto-could-be-the-lead-domino-autonomous-vehicles-to-spur-ma-activity/#337f0c0f65ae.

"Replicated Board") that bore a striking resemblance to – and shared several unique characteristics with – Waymo's highly confidential current-generation LiDAR circuit board, the design of which had been downloaded by Mr. Levandowski before his resignation.

59. The Replicated Board reflects Waymo's highly confidential proprietary LiDAR technology and Waymo trade secrets. Moreover, the Replicated Board is specifically designed to be used in conjunction with many other Waymo trade secrets and in the context of overall LiDAR systems covered by Waymo patents.

60. With greatly heightened suspicion that Otto and Uber were actually using Waymo's intellectual property for their own purposes (and to Waymo's detriment), Waymo endeavored to find a way to confirm whether Defendants were using Waymo's patented and trade secret LiDAR designs. Ultimately, Waymo received such confirmation in response to a public records request it made to the Nevada Governor's Office of Economic Development and Department of Motor Vehicles on February 3, 2016.

61. Among the documents Waymo received on February 9, 2016 in response to that request were submissions made by Otto to Nevada regulatory authorities. In one such submission, dated less than one month after the Otto acquisition and while Uber was refusing to publicly identify the supplier of its LiDAR system,[6] Otto privately represented that it had "developed in house and/or currently deployed" an "[i]n-house custom built 64-laser" LiDAR system. This was the final piece of the puzzle: confirmation that Uber and Otto are in fact using a custom LiDAR system with the same characteristics as Waymo's proprietary system.

H. Waymo Has Been, And Will Be, Severely Harmed By Defendants' Infringement Of Waymo's Patents And Misappropriation Of Waymo's Confidential And Proprietary Trade Secret Information

62. Waymo developed its patented inventions and trade secrets at great expense, and through years of painstaking research, experimentation, and trial and error. If Defendants are not enjoined from their infringement and misappropriation, they will cause severe and irreparable harm to Waymo.

[6] Mike Murphy, "This is the week self-driving cars became real," *Quartz*, Sept. 17, 2016, *available at* https://qz.com/780606/this-is-the-week-self-driving-cars-became-real/.

63. The markets for self-driving vehicles are nascent and on the cusp of rapid development. The impending period of drastic market growth, as autonomous car technology matures and is increasingly commercialized, will set the competitive landscape for the industry going forward. The growth, profitability, and even survival of individual firms will likely be determined by what happens in the next few years. Defendants' exploitation of stolen intellectual property greatly harms Waymo during this embryonic market formation process and deforms the creation of a fair and competitive industry. Allowing the conduct to continue, and awarding monetary compensation after the fact, will not sufficiently unravel the harm caused to Waymo directly and indirectly by Defendants' conduct.

64. With respect to Waymo's trade secrets, there is also the threat that Waymo's confidential and proprietary information will be disclosed by Defendants, which will destroy the trade secret value of the technology. This may occur either voluntarily by Defendants for its own publicity purposes or because a regulatory agency requires disclosure for permitting purposes.

65. With this action, Waymo seeks to vindicate its rights, prevent any further infringement of its patents, preclude any further misuse of its confidential, proprietary, and trade secret information, and obtain compensation for its damages and for Defendants' unjust enrichment resulting from their unlawful conduct.

FIRST CAUSE OF ACTION

Violation of Defense of Trade Secret Act
(Against All Defendants)

66. Waymo incorporates all of the above paragraphs as though fully set forth herein.

67. Waymo owns and possesses certain confidential, proprietary, and trade secret information, as alleged above. One example of the trade secret information is reflected in printed circuit board designs contained in certain design files that Anthony Levandowski downloaded from Waymo's system. Various aspects of the printed circuit board designs for the current generation of Waymo's LiDAR system are Waymo's trade secrets, including the position and orientation of the laser diodes and photodetectors mounted on the printed circuit boards. Waymo's trade secret information also includes the selection, materials, size, position, and

orientation of optical elements that are used to manipulate and modify laser beams that are transmitted and detected by Waymo's current generation LiDAR system. Waymo's trade secret information further includes the resolution profile that is achieved through its proprietary positioning and orientation of laser diodes and optical elements in its current generation LiDAR system, and the know-how associated with using the resolution profile to accurately detect objects in the environment. Another example of Waymo's trade secrets is the rate at which the current generation LiDAR system pulses and fires the laser diodes into the environment, and the know-how associated with using the pulse rate and fire rate to accurately detect objects in the environment. None of these trade secrets is disclosed in any published Waymo patents or patent applications.

68. Waymo's confidential, proprietary, and trade secret information relates to products and services used, sold, shipped and/or ordered in, or intended to be used, sold, shipped and/or ordered in, interstate or foreign commerce.

69. Waymo has taken reasonable measures to keep such information secret and confidential.

70. Waymo has at all times maintained stringent security measures to preserve the secrecy of its LiDAR trade secrets. For example, Waymo restricts access to confidential and proprietary trade secret information to only those who "need to know." That is, employees working on projects unrelated to self-driving cars have not had and do not have access to Waymo's schematics, supply chain information, or other categories of confidential and proprietary information. All networks hosting Waymo's confidential and proprietary information have been and continue to be encrypted and have at all times required passwords and dual-authentication for access. Computers, tablets, and cell phones provided to Waymo employees are encrypted, password protected, and subject to other security measures. And Waymo secures its physical facilities by restricting access and then monitoring actual access with security cameras and guards.

71. Waymo also requires all employees, contractors, consultants, vendors, and manufacturers to sign confidentiality agreements before any confidential or proprietary trade secret information is disclosed to them. Every outside vendor and manufacturer that has received

confidential and proprietary trade secret information related to Waymo's LiDAR technology has executed at least one written non-disclosure agreement. As a further precaution, Waymo purchases the components for its LiDAR systems from numerous, different vendors and conducts the final assembly in-house at Waymo. As a result, no single Waymo vendor has full knowledge of Waymo's proprietary LiDAR systems.

72. Due to these security measures, Waymo's confidential and proprietary trade secret information is not available for others in the automated vehicle industry – or any other industry – to use through any legitimate means.

73. Waymo's confidential, proprietary, and trade secret information derives independent economic value from not being generally known to, and not being readily ascertainable through proper means by, another person who could obtain economic value from the disclosure or use of the information.

74. In violation of Waymo's rights, Defendants misappropriated Waymo's confidential, proprietary and trade secret information in the improper and unlawful manner as alleged herein. Defendants' misappropriation of Waymo's confidential, proprietary, and trade secret information was intentional, knowing, willful, malicious, fraudulent, and oppressive. Defendants have attempted and continue to attempt to conceal their misappropriation.

75. On information and belief, if Defendants are not enjoined, Defendants will continue to misappropriate and use Waymo's trade secret information for their own benefit and to Waymo's detriment.

76. As the direct and proximate result of Defendants' conduct, Waymo has suffered and, if Defendants' conduct is not stopped, will continue to suffer, severe competitive harm, irreparable injury, and significant damages, in an amount to be proven at trial. Because Waymo's remedy at law is inadequate, Waymo seeks, in addition to damages, temporary, preliminary, and permanent injunctive relief to recover and protect its confidential, proprietary, and trade secret information and to protect other legitimate business interests. Waymo's business operates in a competitive market and will continue suffering irreparable harm absent injunctive relief.

77. Waymo has been damaged by all of the foregoing and is entitled to an award of exemplary damages and attorney's fees.

<u>SECOND CAUSE OF ACTION</u>

Violation of California Uniform Trade Secret Act, Cal. Civ. Code § 3426 *et seq.* (Against All Defendants)

78. Waymo incorporates all of the above paragraphs as though fully set forth herein.

79. Waymo's technical information, designs, and other "know how" related to its LiDAR constitute trade secrets as defined by California's Uniform Trade Secrets Act. Waymo owns and possesses certain confidential, proprietary, and trade secret information, as alleged above. One example of the trade secret information is reflected in printed circuit board designs contained in certain design files that Anthony Levandowski downloaded from Waymo's system. Various aspects of the printed circuit board designs for the current generation of Waymo's LiDAR system are Waymo's trade secrets, including the position and orientation of the laser diodes and photodetectors mounted on the printed circuit boards. Waymo's trade secret information also includes the selection, materials, size, position, and orientation of optical elements that are used to manipulate and modify laser beams that are transmitted and detected by Waymo's current generation LiDAR system. Waymo's trade secret information further includes the resolution profile that is achieved through its proprietary positioning and orientation of laser diodes and optical elements in its current generation LiDAR system, and the know-how associated with using the resolution profile to accurately detect objects in the environment. Another example of Waymo's trade secrets is the rate at which the current generation LiDAR system pulses and fires the laser diodes into the environment, and the know-how associated with using the pulse rate and fire rate to accurately detect objects in the environment. None of this information is disclosed in any published Waymo patents or patent applications, and the information has actual or potential independent economic value from not being generally known to the public or other persons who could obtain economic value from their disclosure or use.

80. Waymo's asserted trade secrets are different than Waymo's asserted patent rights. By way of example, only: (i) Waymo's asserted patents relate to a prior generation of Waymo's

proprietary LiDAR designs, whereas Waymo's trade secrets include elements for subsequent and as of today un-patented and confidential LiDAR designs; and (ii) Waymo's trade secrets include specific parameters and measurements for Waymo's LiDAR designs that are not disclosed in any asserted Waymo patents. Examples of trade secret information that is not covered or disclosed by any asserted Waymo patents include the specific parameters or measurements for vertical beam spacing, distribution of beam elevations and orientations, the beams' field of view measurements, the pitch or orientations between diodes, pitch measurements for optical cavities, pulse rates, and fire rates for beam returns.

81. Waymo has undertaken efforts that are reasonable under the circumstances to maintain the secrecy of the trade secrets at issue. These efforts include, but are not limited to, the use of passwords and encryption to protect data on its computers, servers, and source code repositories, the maintenance of a Code of Conduct that emphasizes all employees' duties to maintain the secrecy of Waymo's confidential information, and the use of confidentiality agreements and non-disclosure agreements to require vendors, partners, contractors, and employees to maintain the secrecy of Waymo's confidential information.

82. Defendants knew or should have known under the circumstances that the information misappropriated by Defendants were trade secrets.

83. Defendants misappropriated and threaten to further misappropriate trade secrets at least by acquiring trade secrets with knowledge of or reason to know that the trade secrets were acquired by improper means, and Defendants are using and threatening to use the trade secrets acquired by improper means without Waymo's knowledge or consent.

84. As a direct and proximate result of Defendants' conduct, Waymo is threatened with injury and has been injured in an amount in excess of the jurisdictional minimum of this Court and that will be proven at trial. Waymo has also incurred, and will continue to incur, additional damages, costs and expenses, including attorney's fees, as a result of Defendants' misappropriation. As a further proximate result of the misappropriation and use of Waymo's trade secrets, Defendants were unjustly enriched.

85. The aforementioned acts of Defendants were willful, malicious and fraudulent. Waymo is therefore entitled to exemplary damages under California Civil Code § 3426.3(c).

86. Defendants' conduct constitutes transgressions of a continuing nature for which Waymo has no adequate remedy at law. Unless and until enjoined and restrained by order of this Court, Defendants will continue to retain and use Waymo's trade secret information to enrich themselves and divert business from Waymo. Pursuant to California Civil Code § 3426.2, Waymo is entitled to an injunction against the misappropriation and continued threatened misappropriation of trade secrets as alleged herein and further asks the Court to restrain Defendants from using all trade secret information misappropriated from Waymo and to return all trade secret information to Waymo.

87. Pursuant to California Civil Code § 3426.4 and related law, Waymo is entitled to an award of attorneys' fees for Defendants' misappropriation of trade secrets.

THIRD CAUSE OF ACTION

Infringement of Patent No. 8,836,922
(Against All Defendants)

88. Waymo incorporates all of the above paragraphs as though fully set forth herein.

89. The '922 patent, entitled "Devices and Methods for a Rotating LIDAR platform with a Shared Transmit/Receive Path," was duly and lawfully issued on September 16, 2014. A true and correct copy of the '922 patent is attached to this Complaint as Exhibit A.

90. Waymo is the owner of all rights, title, and interest in the '922 patent, including the right to bring this suit for injunctive relief and damages.

91. The '922 patent is valid and enforceable.

92. Defendants have infringed, and continue to infringe, literally and/or through the doctrine of equivalents, one or more claims of the '922 patent, including but not limited to claim 1, pursuant to 35 U.S.C. § 271(a), by making, using, selling, offering to sell, and/or importing within the United States, without authority, certain LiDAR devices ("Accused LiDAR Devices").

93. On information and belief, the Accused LiDAR Devices, such as those using the Replicated Board, comprise a LiDAR device with a single lens that transmits light pulses

originating from one or more light sources and receiving light pulses that are then detected by one or more detectors. Defendants infringe at least claim 1 of the ’922 patent for at least the following reasons:

94. Defendants’ Accused LiDAR Devices are LiDAR devices.

95. On information and belief, Defendants’ Accused LiDAR Devices have a lens mounted to a housing, wherein the housing is configured to rotate about an axis and has an interior space that includes a transmit block, a receive block, a transmit path, and a receive path, wherein the transmit block has an exit aperture in a wall that comprises a reflective surface, wherein the receive block has an entrance aperture, wherein the transmit path extends from the exit aperture to the lens, and wherein the receive path extends from the lens to the entrance aperture via the reflective surface.

96. On information and belief, Defendants’ Accused LiDAR Devices have a plurality of light sources in the transmit block, wherein the plurality of light sources are configured to emit a plurality of light beams through the exit aperture in a plurality of different directions, the light beams comprising light having wavelengths in a wavelength range.

97. On information and belief, Defendants’ Accused LiDAR Devices have a plurality of detectors in the receive block, wherein the plurality of detectors are configured to detect light having wavelengths in the wavelength range.

98. On information and belief, Defendants’ Accused LiDAR Devices have a lens that is configured to receive the light beams via the transmit path, collimate the light beams for transmission into an environment of the LIDAR device, collect light comprising light from one or more of the collimated light beams reflected by one or more of the collimated light beams reflected by one or more objects in the environment of the LIDAR device, and focus the collected light onto the detectors via the receive path.

99. Defendants’ infringement of the ’922 patent has been willful and deliberate because Defendants knew or should have known about the ’922 patent and their infringement of that patent but acted despite an objectively high likelihood that such acts would infringe the patent. On information and belief, at least three of the individuals who developed the Accused LiDAR

Devices are named inventors of the ’922 patent who – while Waymo employees, and on behalf of Waymo, which owns the ’922 patent – were involved in the conception and/or reduction to practice of the ’922 patent and have had knowledge of the patent since it issued in September 2014.

100. As the direct and proximate result of Defendants’ conduct, Waymo has suffered and, if Defendants’ conduct is not stopped, will continue to suffer, severe competitive harm, irreparable injury, and significant damages, in an amount to be proven at trial. Because Waymo’s remedy at law is inadequate, Waymo seeks, in addition to damages, temporary, preliminary, and permanent injunctive relief. Waymo’s business operates in a competitive market and will continue suffering irreparable harm absent injunctive relief.

FOURTH CAUSE OF ACTION

Infringement of Patent No. 9,368,936
(Against All Defendants)

101. Waymo incorporates all of the above paragraphs as though fully set forth herein.

102. The ’936 patent, entitled “Laser Diode Firing System,” was duly and lawfully issued on June 14, 2016. A true and correct copy of the ’936 patent is attached to this Complaint as Exhibit B.

103. Waymo is the owner of all rights, title, and interest in the ’936 patent, including the right to bring this suit for injunctive relief and damages.

104. The ’936 patent is valid and enforceable.

105. Defendants have infringed, and continue to infringe, literally and/or through the doctrine of equivalents, one or more claims of the ’936 patent, including but not limited to claim 1, pursuant to 35 U.S.C. § 271(a), by making, using, selling, offering to sell, and/or importing within the United States, without authority, the Accused LiDAR devices.

106. On information and belief, Defendants’ Accused LiDAR Devices, such as those using the Replicated Board, comprise a laser diode firing circuit for a LiDAR device, which utilizes an inductor and a charging capacitor, where both the charging and discharge path are

controllable via a single transistor and gate signal. Defendants infringe at least claim 1 of the '936 patent for at least the following reasons:

107. On information and belief, Defendants' Accused LiDAR Devices have a voltage source.

108. On information and belief, Defendants' Accused LiDAR Devices have an inductor coupled to the voltage source, wherein the inductor is configured to store energy in a magnetic field.

109. On information and belief, Defendants' Accused LiDAR Devices have a diode or equivalent coupled to the voltage source via the inductor.

110. On information and belief, Defendants' Accused LiDAR Devices have a transistor configured to be turned on and turned off by a control signal.

111. On information and belief, Defendants' Accused LiDAR Devices have a light emitting element coupled to the transistor.

112. On information and belief, Defendants' Accused LiDAR Devices Circuit Boards have a capacitor coupled to a charging path and a discharge path, wherein the charging path includes the inductor and the diode, and wherein the discharge path includes the transistor and the light emitting element.

113. On information and belief, Defendants' Accused LiDAR Devices have, responsive to the transistor being turned off, a capacitor configured to charge via the charging path such that a voltage across the capacitor increases from a lower voltage level to a higher voltage level and an inductor configured to release energy stored in the magnetic field such that a current through the inductor decreases from a higher current level to a lower current level.

114. On information and belief, Defendants' Accused LiDAR Devices have, responsive to the transistor being turned on, a capacitor configured to discharge through the discharge path such that the light emitting element emits a pulse of light and the voltage across the capacitor decreases from the higher voltage level to the lower voltage level and the inductor is configured to store energy in the magnetic field such that the current through the inductor increases from the lower current level to the higher current level.

115. As the direct and proximate result of Defendants' conduct, Waymo has suffered and, if Defendants' conduct is not stopped, will continue to suffer, severe competitive harm, irreparable injury, and significant damages, in an amount to be proven at trial. Because Waymo's remedy at law is inadequate, Waymo seeks, in addition to damages, temporary, preliminary, and permanent injunctive relief. Waymo's business operates in a competitive market and will continue suffering irreparable harm absent injunctive relief.

FIFTH CAUSE OF ACTION

Infringement of Patent No. 9,086,273
(Against All Defendants)

116. Waymo incorporates all of the above paragraphs as though fully set forth herein.

117. The '273 patent, entitled "Microrod Compression of Laser Beam in Combination with Transmit Lens," was duly and lawfully issued on July 21, 2015. A true and correct copy of the '273 patent is attached to this Complaint as Exhibit C.

118. Waymo is the owner of all rights, title, and interest in the '273 patent, including the right to bring this suit for injunctive relief and damages.

119. The '273 patent is valid and enforceable.

120. Defendants have infringed, and continue to infringe, literally and/or through the doctrine of equivalents, one or more claims of the '273 patent, including but not limited to claim 1, pursuant to 35 U.S.C. § 271(a), by making, using, selling, offering to sell, and/or importing within the United States, without authority, the Accused LiDAR Devices.

121. On information and belief, Defendants' Accused Lidar Devices, such as those using the Replicated Board and the Uber Custom LiDAR described in Uber's Nevada regulatory filing, comprise a LiDAR device with a single lens that both (i) collimates the light from one or more light sources to provide collimated light for transmission into an environment of the LiDAR device, and (ii) focuses the reflected light onto one or more photodetectors, and with cylindrical lenses associated with each laser diode that pre-collimate the uncollimated laser beam. Defendants infringe at least claim 1 of the '273 patent for at least the following reasons:

122. On information and belief, Defendants' Accused LiDAR Devices are LiDAR devices.

123. On information and belief, Defendants' Accused LiDAR Devices have at least one laser diode, wherein the at least one laser diode is configured to emit an uncollimated laser beam comprising light in a narrow wavelength range, wherein the uncollimated laser beam has a first divergence in a first direction and a second divergence in a second direction, and wherein the first divergence is greater than the second divergence.

124. On information and belief, Defendants' Accused LiDAR Devices have at least one cylindrical lens, wherein the at least one cylindrical lens is configured to pre-collimate the uncollimated laser beam that has a third divergence in the first direction and a fourth divergence in the second direction, wherein the third divergence is less than the fourth divergence and the fourth divergence is substantially equal to the second divergence.

125. On information and belief, Defendants' Accused LiDAR Devices have at least one detector, wherein the at least one detector is configured to detect light having wavelengths in the narrow wavelength range.

126. On information and belief, Defendants' Accused LiDAR Devices have an objective lens, wherein the objective lens is configured to (i) collimate the partially collimated laser beam for transmission into an environment of the LiDAR device and (ii) focus object reflected light onto the at least one detector, wherein the object-reflected light comprises light from the collimated laser beam in the environment of the LiDAR device.

127. Defendants' infringement of the '273 patent has been willful and deliberate because Defendants knew or should have known about the '273 patent and their infringement of that patent but acted despite an objectively high likelihood that such acts would infringe the patent. At least one individual who developed the Accused LiDAR Devices is a named inventor on the '273 patent who – while a Waymo employee, and on behalf of Waymo, which owns the '273 patent – was involved in the conception and/or reduction to practice of the '273 patent and therefore has had knowledge of the patent since it issued in July 21, 2015.

128. As the direct and proximate result of Defendants' conduct, Waymo has suffered and, if Defendants' conduct is not stopped, will continue to suffer, severe competitive harm, irreparable injury, and significant damages, in an amount to be proven at trial. Because Waymo's remedy at law is inadequate, Waymo seeks, in addition to damages, temporary, preliminary, and permanent injunctive relief. Waymo's business operates in a competitive market and will continue suffering irreparable harm absent injunctive relief.

SIXTH CAUSE OF ACTION

Violation of California Bus. & Prof. Code § 17200
(Against All Defendants)

129. Waymo incorporates all of the above paragraphs as though fully set forth herein.

130. Defendants engaged in unlawful, unfair, and fraudulent business acts and practices. Such acts and practices include, but are not limited to, misappropriating Waymo's confidential and proprietary information.

131. Defendants' business acts and practices were unlawful as described above.

132. Defendants' business acts and practices were fraudulent in that a reasonable person would likely be deceived by their material misrepresentations and omissions. Defendants have acquired and used Waymo's confidential and proprietary trade secret information through material misrepresentations and omissions.

133. Defendants' business acts and practices were unfair in that the substantial harm suffered by Waymo outweighs any justification that Defendants may have for engaging in those acts and practices.

134. Waymo has been harmed as a result of Defendants' unlawful, unfair, and fraudulent business acts and practices. Waymo is entitled to (a) recover restitution, including without limitation, all benefits that Defendants received as a result of their unlawful, unfair, and fraudulent business acts and practices and (b) an injunction restraining Defendants from engaging in further acts of unfair competition.

PRAYER FOR RELIEF

WHEREFORE, Waymo respectfully requests the following relief:

135. Judgment in Waymo's favor and against Defendants on all causes of action alleged herein;

136. For damages in an amount to be further proven at trial, including trebling of all damages awarded with respect to infringement of the '922 and '273 patents;

137. For preliminary and permanent injunctive relief;

138. For judgment that this is an exceptional case;

139. For punitive damages;

140. For restitution;

141. For costs of suit incurred herein;

142. For prejudgment interest;

143. For attorneys' fees and costs; and

144. For such other and further relief as the Court may deem to be just and proper.

DEMAND FOR JURY TRIAL

Waymo hereby demands trial by jury for all causes of action, claims, or issues in this action that are triable as a matter of right to a jury

DATED: February 23, 2017

QUINN EMANUEL URQUHART & SULLIVAN, LLP

By */s/ Charles K. Verhoeven*
Charles K. Verhoeven
Attorneys for WAYMO LLC

EXHIBIT A

US008836922B1

(12) **United States Patent**
Pennecot et al.

(10) **Patent No.: US 8,836,922 B1**
(45) **Date of Patent: Sep. 16, 2014**

(54) **DEVICES AND METHODS FOR A ROTATING LIDAR PLATFORM WITH A SHARED TRANSMIT/RECEIVE PATH**

(71) Applicant: **Google Inc.**, Mountain View, CA (US)

(72) Inventors: **Gaetan Pennecot**, San Francisco, CA (US); **Pierre-Yves Droz**, Los Altos, CA (US); **Drew Eugene Ulrich**, San Francisco, CA (US); **Daniel Gruver**, San Francisco, CA (US); **Zachary Morriss**, San Francisco, CA (US); **Anthony Levandowski**, Berkeley, CA (US)

(73) Assignee: **Google Inc.**, Mountain View, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **13/971,606**

(22) Filed: **Aug. 20, 2013**

(51) **Int. Cl.**
G01C 3/08 (2006.01)
G01S 17/02 (2006.01)

(52) **U.S. Cl.**
CPC ***G01S 17/02*** (2013.01)
USPC **356/4.01**; 356/3.01; 356/5.01; 356/5.09; 356/4.07; 356/9; 356/625; 356/337; 356/342; 356/28; 356/28.5

(58) **Field of Classification Search**
CPC G01C 3/08; G01C 15/002; G01C 11/025; G01C 15/02; G01C 21/30; G01S 17/89; G01S 7/4817; G01S 17/42; G01S 17/50; G01S 17/158; G01N 15/0205; G01N 15/1459; G01N 21/29; G01N 2015/1486; G01N 21/53; G01N 21/538; G01N 2021/4709; G01N 21/21; G01P 3/36; G01P 5/26; G01P 3/366
USPC 356/4.01, 3.01, 4.07, 5.01, 5.09, 9, 625, 356/337–342, 28, 28.5
See application file for complete search history.

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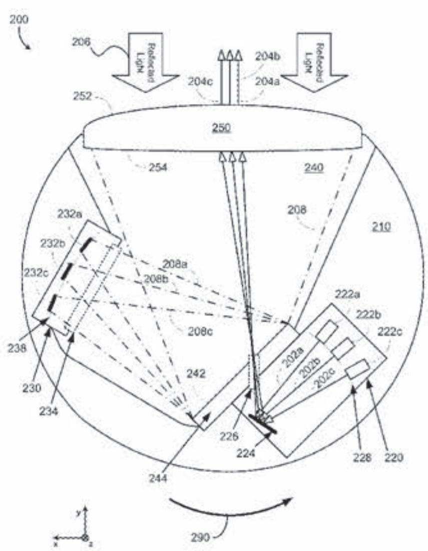
Primary Examiner — Isam Alsomiri
Assistant Examiner — Samantha K Abraham
(74) *Attorney, Agent, or Firm* — McDonnell Boehnen Hulbert & Berghoff LLP

(57) **ABSTRACT**

A LIDAR device may transmit light pulses originating from one or more light sources and may receive reflected light pulses that are then detected by one or more detectors. The LIDAR device may include a lens that both (i) collimates the light from the one or more light sources to provide collimated light for transmission into an environment of the LIDAR device and (ii) focuses the reflected light onto the one or more detectors. The lens may define a curved focal surface in a transmit path of the light from the one or more light sources and a curved focal surface in a receive path of the one or more detectors. The one or more light sources may be arranged along the curved focal surface in the transmit path. The one or more detectors may be arranged along the curved focal surface in the receive path.

18 Claims, 11 Drawing Sheets



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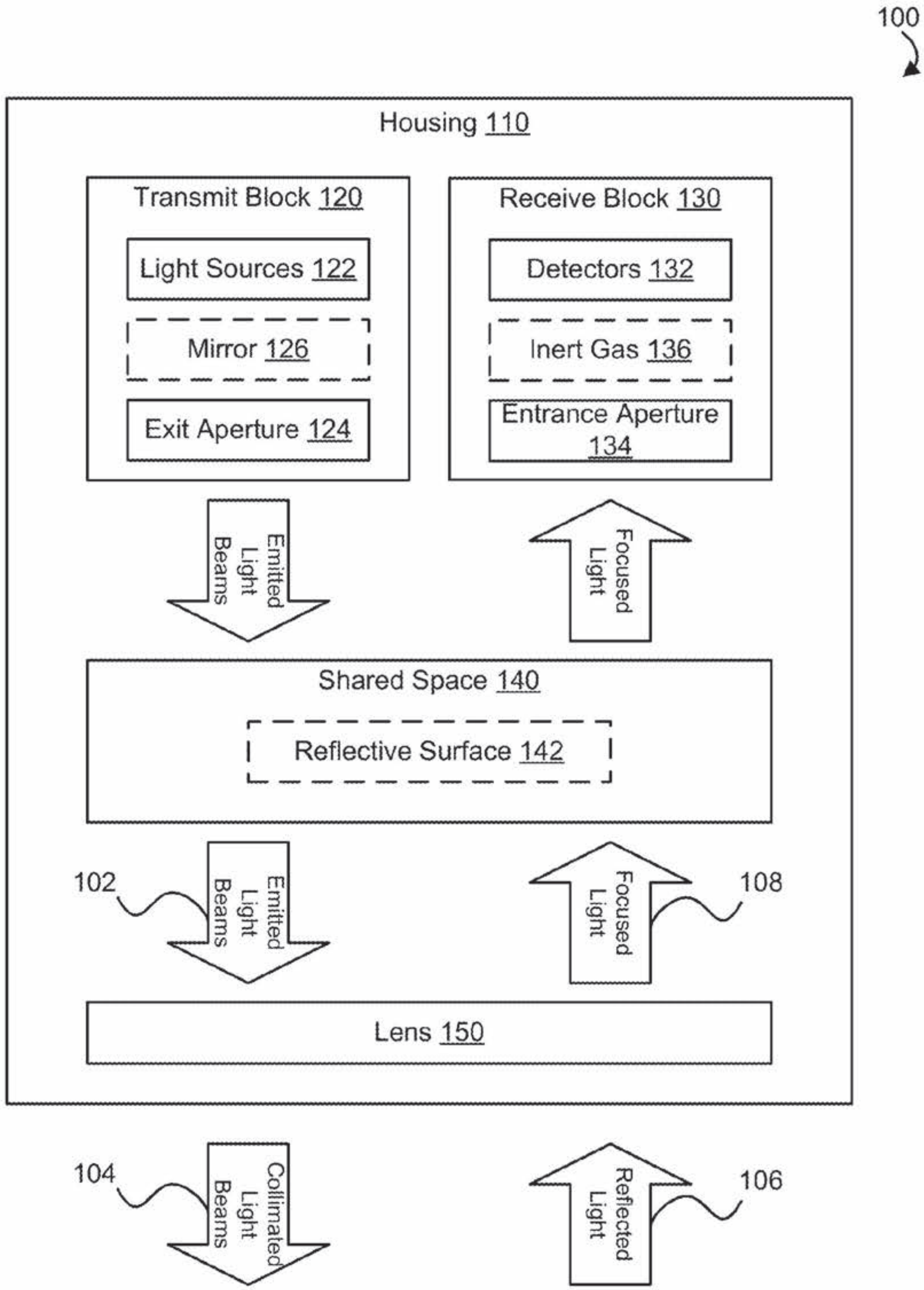
100
Housing 110
Transmit Block 120
Light Sources 122
Mirror 126
Exit Aperture 124
Receive Block 130
Detectors 132
Inert Gas 136
Entrance Aperture 134
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Focused Light
Shared Space 140
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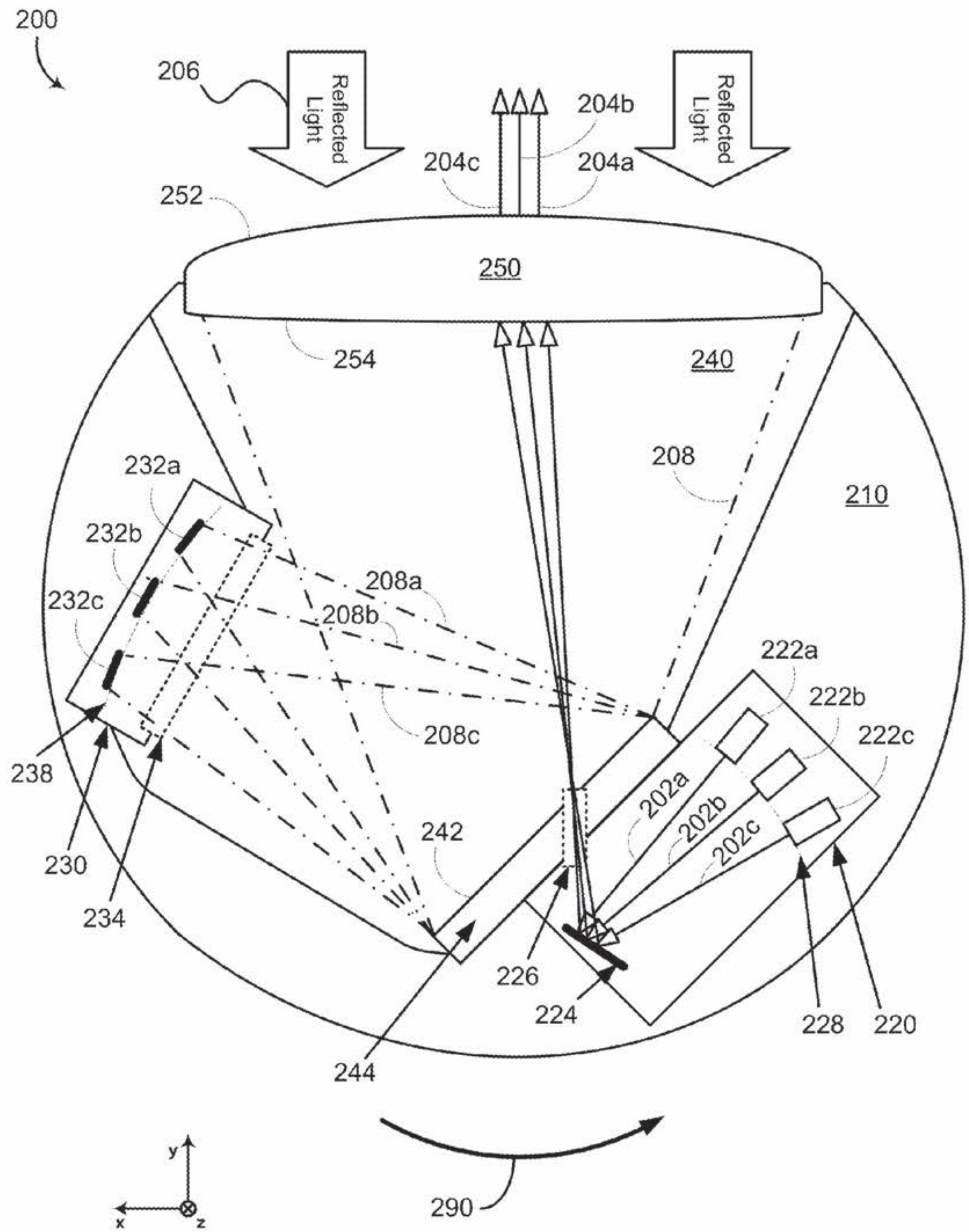
102
Emitted Light Beams
Focused Light
108
Lens 150
104
Collimated Light Beams
Reflected Light
106

FIG. 1


200
206
Reflected Light
Reflected Light
204b
204c
204a
252
250
254
240
208
210
232a
232b
232c
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208b
222a
222b
222c
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238
242
230
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226
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228
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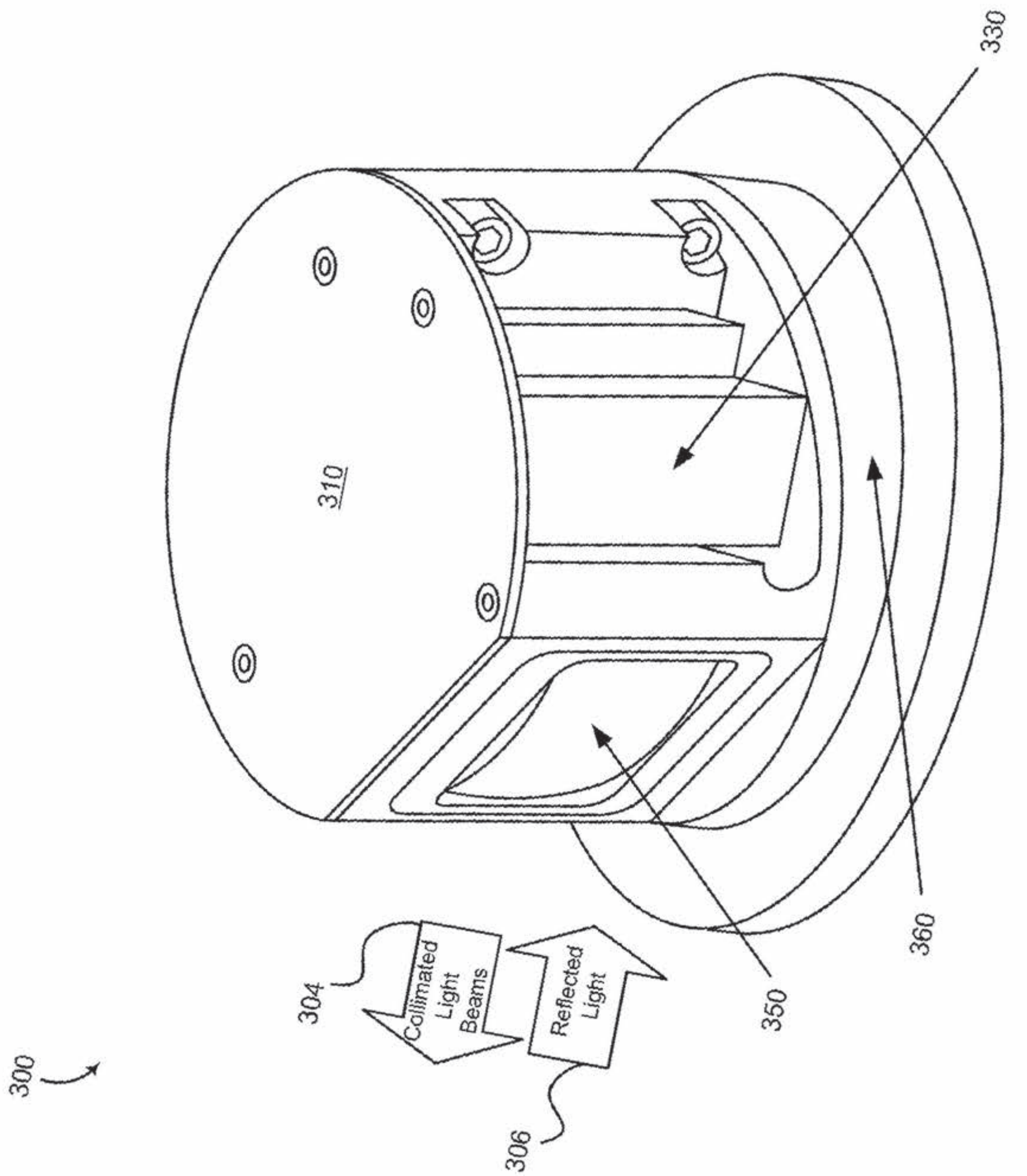
290
y
x
z

FIG. 2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304
Collimated Light Beams
306
Reflected Light
310
330
350
360

FIG. 3A

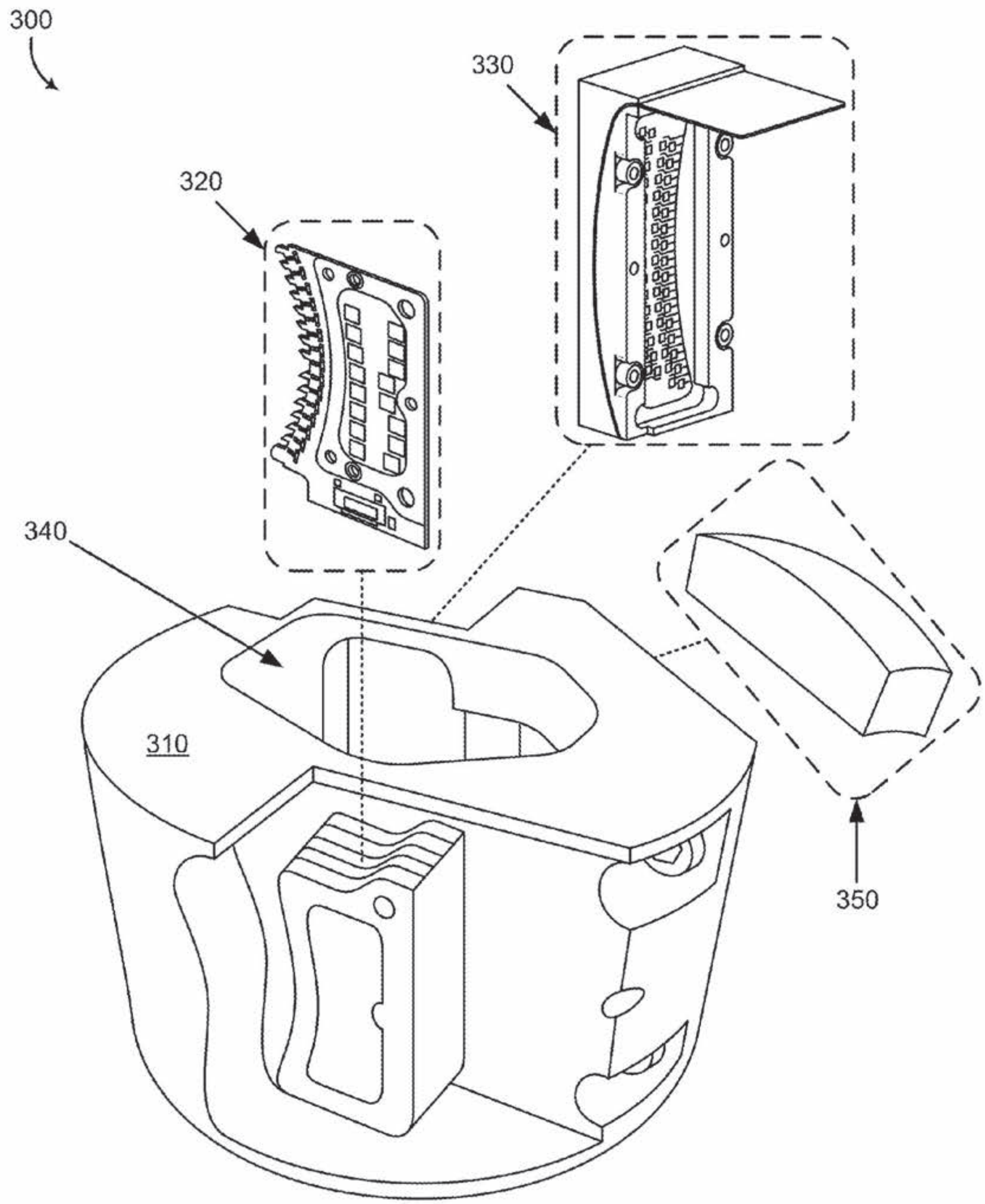


FIG. 3B

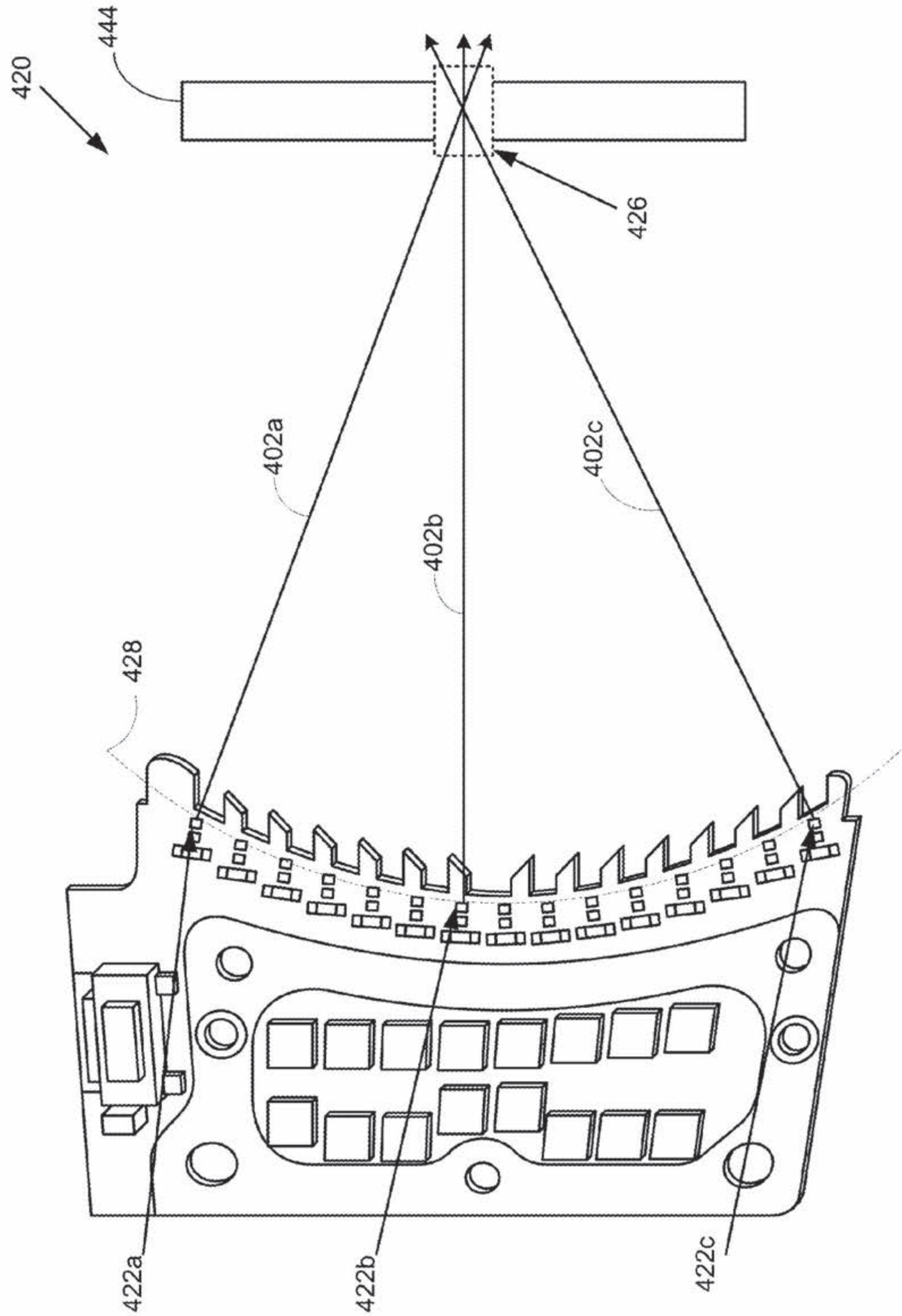


FIG. 4

FIG. 5A

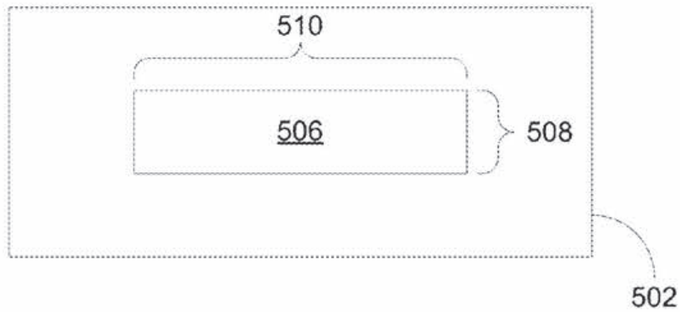


FIG. 5B

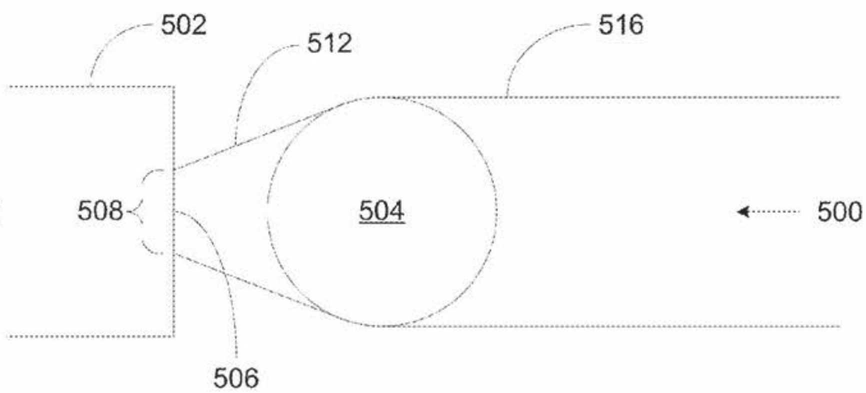
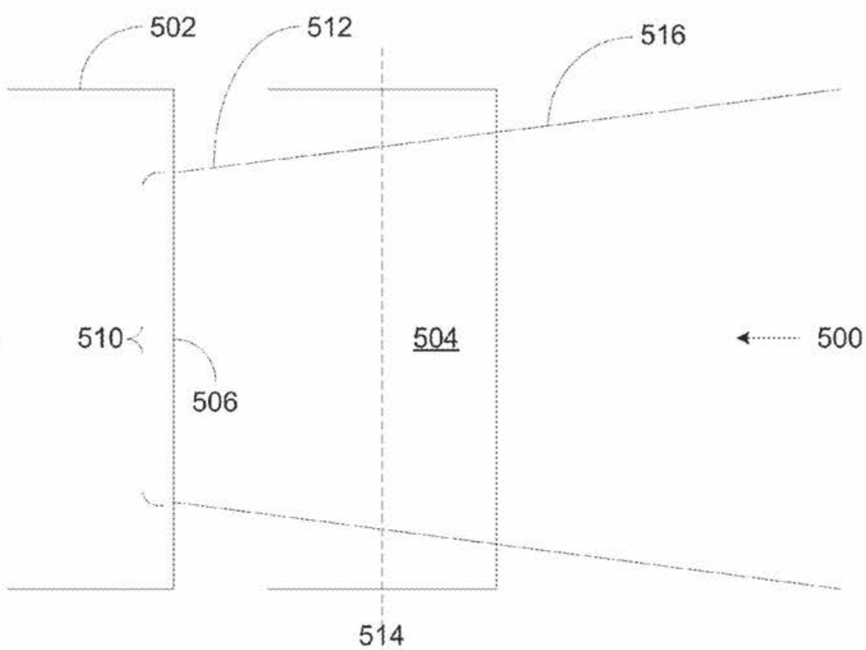


FIG. 5C



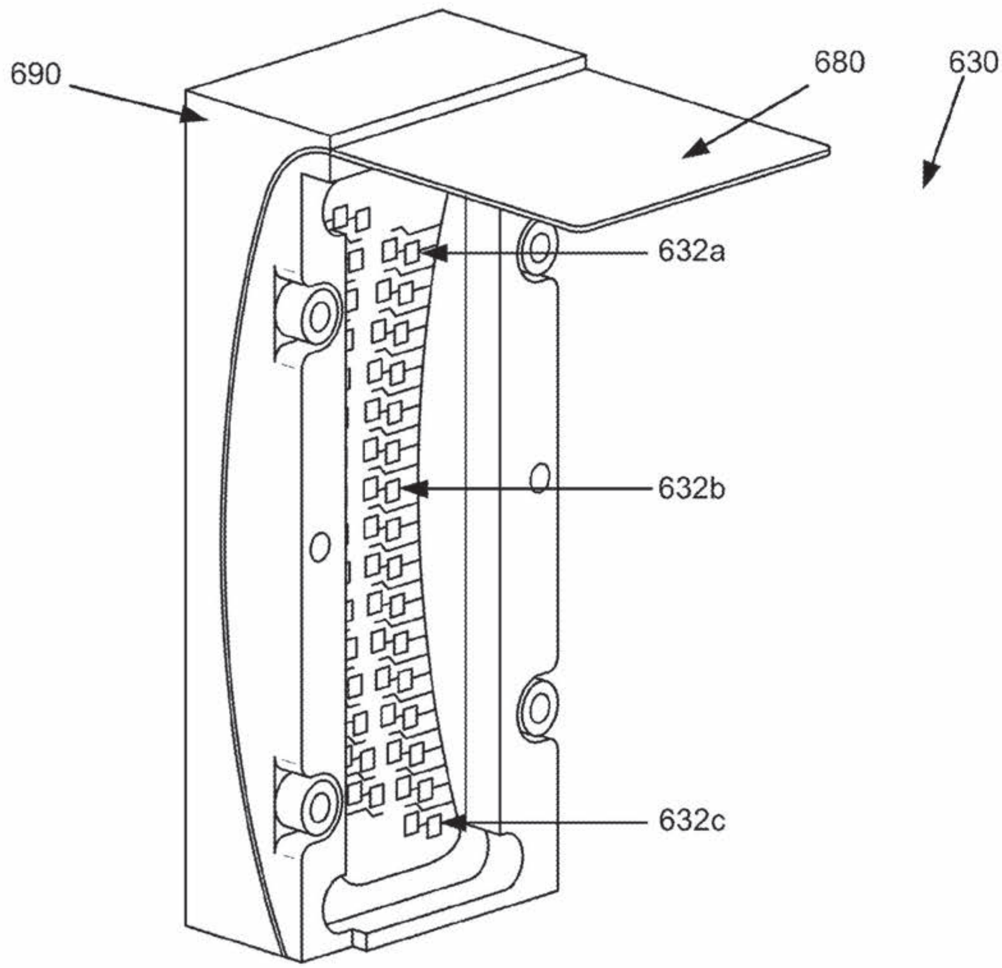
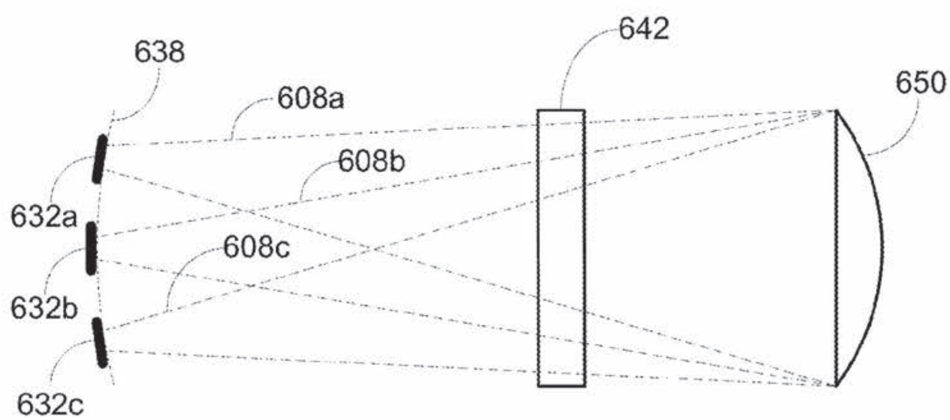

690
680
630
632a
632b
632c

FIG. 6A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638
608a
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608b
632a
608c
632b
632c

FIG. 6B

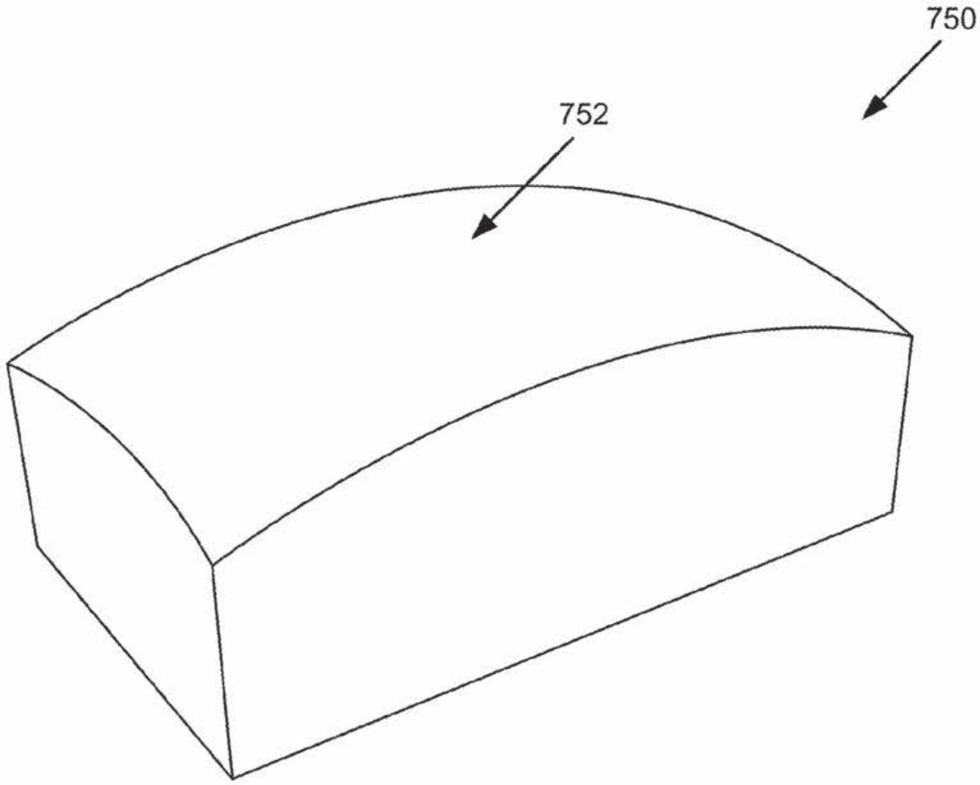

FIG. 7A

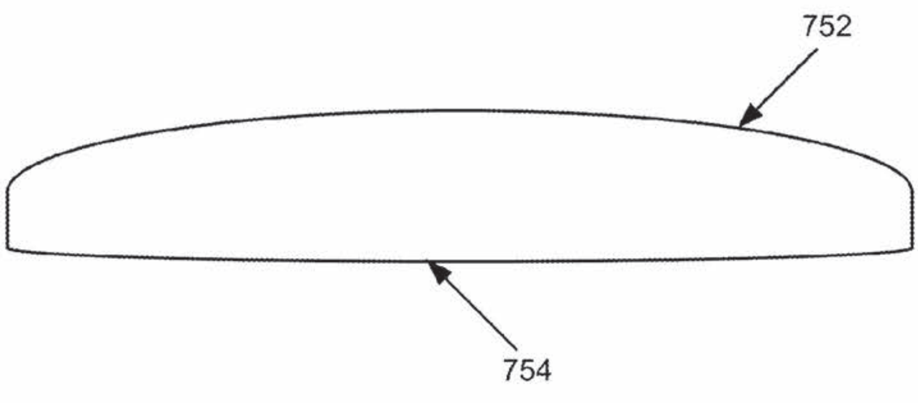

FIG. 7B

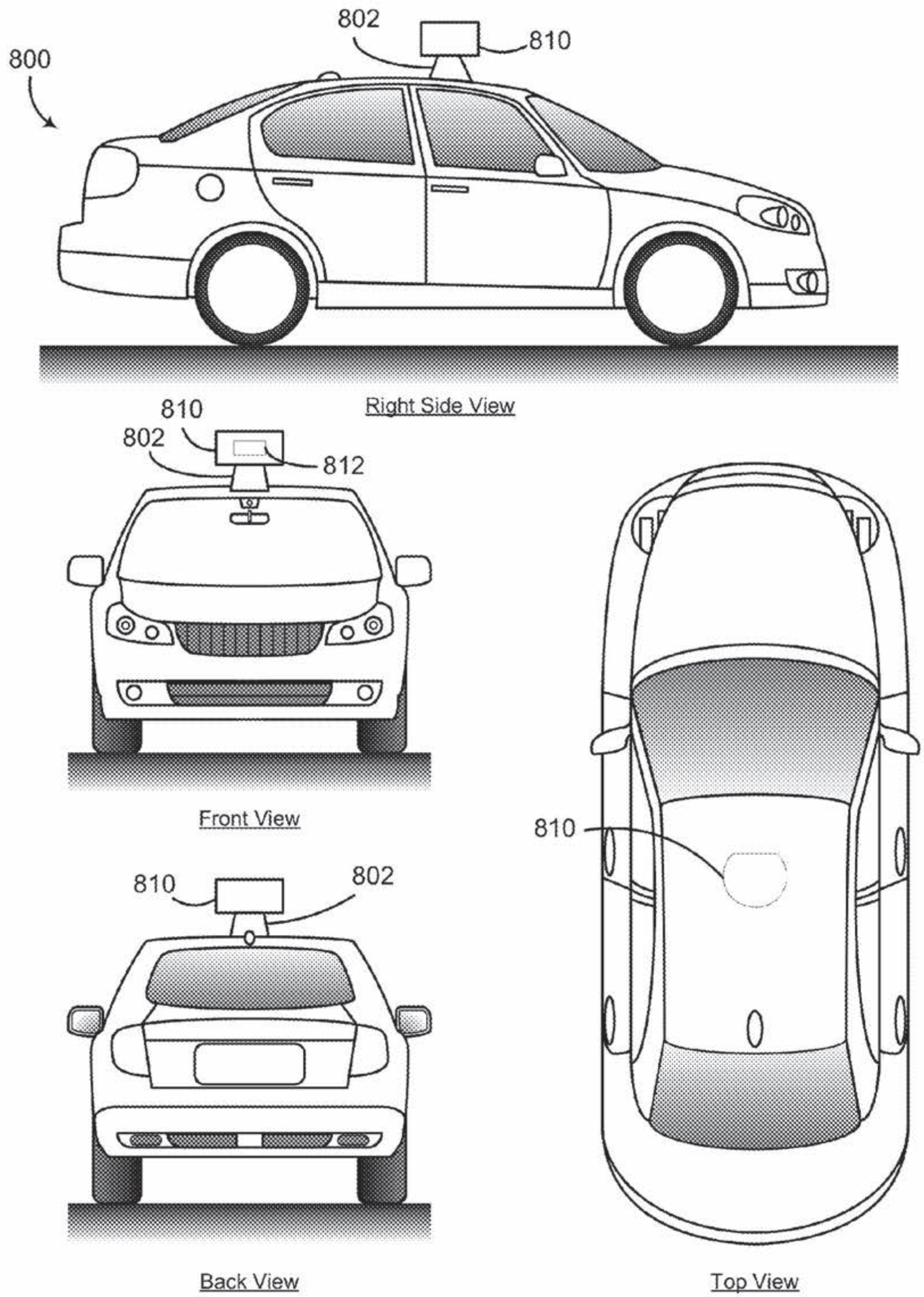
800
802
810
Right Side View
810
802
812
Front View
810
802
Back View
810
Top View

FIG. 8A

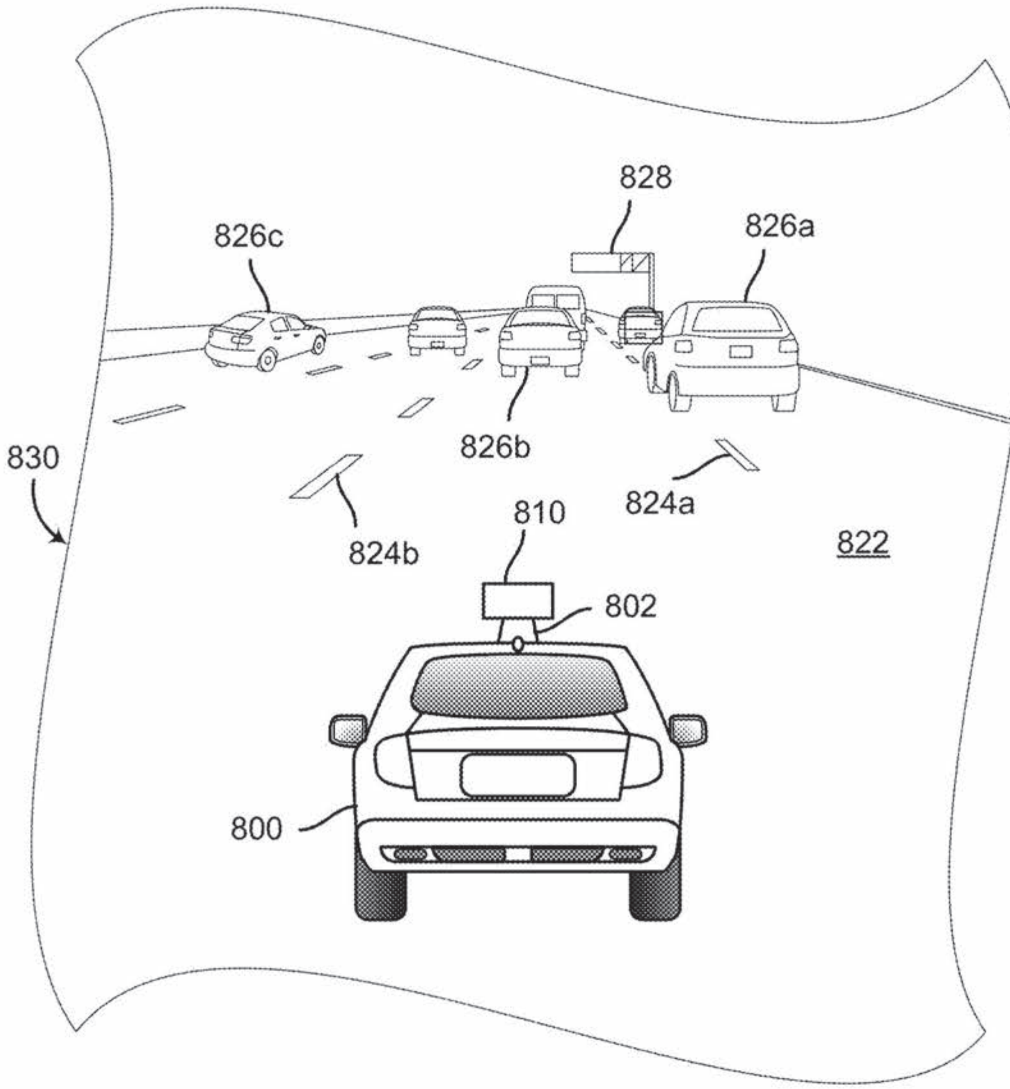

FIG. 8B

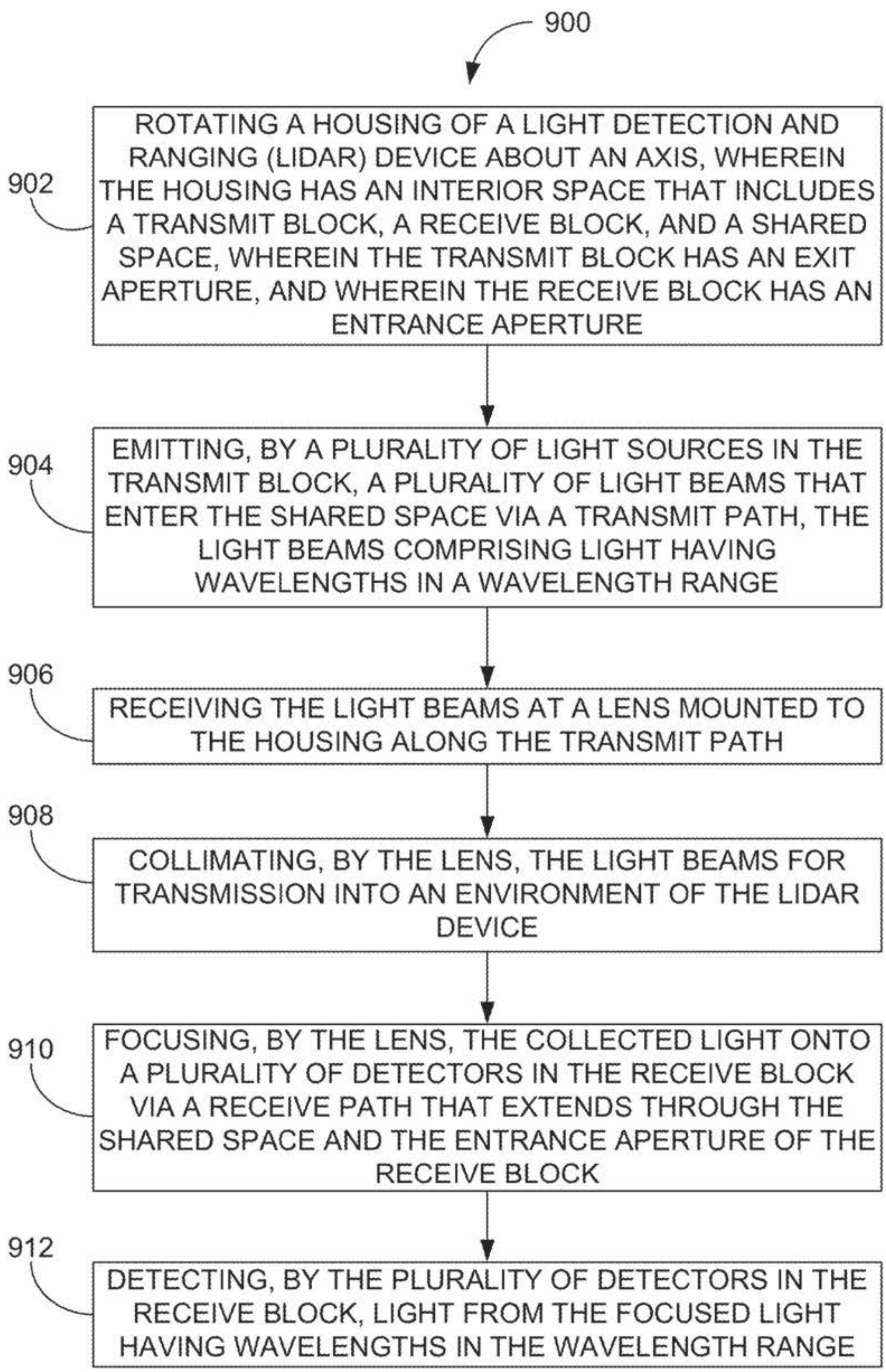
900
902
ROTATING A HOUSING OF A LIGHT DETECTION AND RANGING (LIDAR) DEVICE ABOUT AN AXIS, WHEREIN THE HOUSING HAS AN INTERIOR SPACE THAT INCLUDES A TRANSMIT BLOCK, A RECEIVE BLOCK, AND A SHARED SPACE, WHEREIN THE TRANSMIT BLOCK HAS AN EXIT APERTURE, AND WHEREIN THE RECEIVE BLOCK HAS AN ENTRANCE APERTURE
904
EMITTING, BY A PLURALITY OF LIGHT SOURCES IN THE TRANSMIT BLOCK, A PLURALITY OF LIGHT BEAMS THAT ENTER THE SHARED SPACE VIA A TRANSMIT PATH, THE LIGHT BEAMS COMPRISING LIGHT HAVING WAVELENGTHS IN A WAVELENGTH RANGE
906
RECEIVING THE LIGHT BEAMS AT A LENS MOUNTED TO THE HOUSING ALONG THE TRANSMIT PATH
908
COLLIMATING, BY THE LENS, THE LIGHT BEAMS FOR TRANSMISSION INTO AN ENVIRONMENT OF THE LIDAR DEVICE
910
FOCUSING, BY THE LENS, THE COLLECTED LIGHT ONTO A PLURALITY OF DETECTORS IN THE RECEIVE BLOCK VIA A RECEIVE PATH THAT EXTENDS THROUGH THE SHARED SPACE AND THE ENTRANCE APERTURE OF THE RECEIVE BLOCK
912
DETECTING, BY THE PLURALITY OF DETECTORS IN THE RECEIVE BLOCK, LIGHT FROM THE FOCUSED LIGHT HAVING WAVELENGTHS IN THE WAVELENGTH RANGE

Figure 9

DEVICES AND METHODS FOR A ROTATING LIDAR PLATFORM WITH A SHARED TRANSMIT/RECEIVE PATH

BACKGROUND

Unless otherwise indicated herein, the materials described in this section are not prior art to the claims in this application and are not admitted to be prior art by inclusion in this section.

Vehicles can be configured to operate in an autonomous mode in which the vehicle navigates through an environment with little or no input from a driver. Such autonomous vehicles can include one or more sensors that are configured to detect information about the environment in which the vehicle operates.

One such sensor is a light detection and ranging (LIDAR) device. A LIDAR can estimates distance to environmental features while scanning through a scene to assemble a "point cloud" indicative of reflective surfaces in the environment. Individual points in the point cloud can be determined by transmitting a laser pulse and detecting a returning pulse, if any, reflected from an object in the environment, and determining the distance to the object according to the time delay between the transmitted pulse and the reception of the reflected pulse. A laser, or set of lasers, can be rapidly and repeatedly scanned across a scene to provide continuous real-time information on distances to reflective objects in the scene. Combining the measured distances and the orientation of the laser(s) while measuring each distance allows for associating a three-dimensional position with each returning pulse. In this way, a three-dimensional map of points indicative of locations of reflective features in the environment can be generated for the entire scanning zone.

SUMMARY

In one example, a light detection and ranging (LIDAR) device is provided that includes a housing configured to rotate about an axis. The housing has an interior space that includes a transmit block, a receive block, and a shared space. The transmit block has an exit aperture and the receive block has an entrance aperture. The LIDAR device also includes a plurality of light sources in the transmit block. The plurality of light sources is configured to emit a plurality of light beams that enter the shared space through the exit aperture and traverse the shared space via a transmit path. The light beams include light having wavelengths in a wavelength range. The LIDAR device also includes a plurality of detectors in the receive block. The plurality of detectors is configured to detect light having wavelengths in the wavelength range. The LIDAR device also includes a lens mounted to the housing. The lens is configured to (i) receive the light beams via the transmit path, (ii) collimate the light beams for transmission into an environment of the LIDAR device, (iii) collect light that includes light from one or more of the collimated light beams reflected by one or more objects in the environment of the LIDAR device, and (iv) focus the collected light onto the detectors via a receive path that extends through the shared space and the entrance aperture of the receive block.

In another example, a method is provided that involves rotating a housing of a light detection and ranging (LIDAR) device about an axis. The housing has an interior space that includes a transmit block, a receive block, and a shared space. The transmit block has an exit aperture and the receive block has an entrance aperture. The method further involves emitting a plurality of light beams by a plurality of light sources in the transmit block. The plurality of light beams enter the shared space via a transmit path. The light beams include light having wavelengths in a wavelength range. The method further involves receiving the light beams at a lens mounted to the housing along the transmit path. The method further involves collimating, by the lens, the light beams for transmission into an environment of the LIDAR device. The method further involves collecting, by the lens, light from one or more of the collimated light beams reflected by one or more objects in the environment of the LIDAR device. The method further involves focusing, by the lens, the collected light onto a plurality of detectors in the receive block via a receive path that extends through the shared space and the entrance aperture of the receive block. The method further involves detecting, by the plurality of detectors in the receive block, light from the focused light having wavelengths in the wavelength range.

These as well as other aspects, advantages, and alternatives, will become apparent to those of ordinary skill in the art by reading the following detailed description, with reference where appropriate to the accompanying figures.

BRIEF DESCRIPTION OF THE FIGURES

FIG. **1** is a block diagram of an example LIDAR device.

FIG. **2** is a cross-section view of an example LIDAR device.

FIG. **3**A is a perspective view of an example LIDAR device fitted with various components, in accordance with at least some embodiments described herein

FIG. **3**B is a perspective view of the example LIDAR device shown in FIG. **3**A with the various components removed to illustrate interior space of the housing.

FIG. **4** illustrates an example transmit block, in accordance with at least some embodiments described herein.

FIG. **5**A is a view of an example light source, in accordance with an example embodiment.

FIG. **5**B is a view of the light source of FIG. **5**A in combination with a cylindrical lens, in accordance with an example embodiment.

FIG. **5**C is another view of the light source and cylindrical lens combination of FIG. **5**B, in accordance with an example embodiment.

FIG. **6**A illustrates an example receive block, in accordance with at least some embodiments described herein.

FIG. **6**B illustrates a side view of three detectors included in the receive block of FIG. **6**A.

FIG. **7**A illustrates an example lens with an aspheric surface and a toroidal surface, in accordance with at least some embodiments described herein.

FIG. **7**B illustrates a cross-section view of the example lens **750** shown in FIG. **7**A.

FIG. **8**A illustrates an example LIDAR device mounted on a vehicle, in accordance with at least some embodiments described herein.

FIG. **8**B illustrates a scenario where the LIDAR device shown in FIG. **8**A is scanning an environment that includes one or more objects, in accordance with at least some embodiments described herein.

FIG. **9** is a flowchart of a method, in accordance with at least some embodiments described herein.

DETAILED DESCRIPTION

The following detailed description describes various features and functions of the disclosed systems, devices and methods with reference to the accompanying figures. In the figures, similar symbols identify similar components, unless

context dictates otherwise. The illustrative system, device and method embodiments described herein are not meant to be limiting. It may be readily understood by those skilled in the art that certain aspects of the disclosed systems, devices and methods can be arranged and combined in a wide variety of different configurations, all of which are contemplated herein.

A light detection and ranging (LIDAR) device may transmit light pulses originating from a plurality of light sources and may receive reflected light pulses that are then detected by a plurality of detectors. Within examples described herein, a LIDAR device is provided that includes a transmit/receive lens that both collimates the light from the plurality of light sources and focuses the reflected light onto the plurality of detectors. By using a transmit/receive lens that performs both of these functions, instead of a transmit lens for collimating and a receive lens for focusing, advantages with respect to size, cost, and/or complexity can be provided.

The LIDAR device comprises a housing that is configured to rotate about an axis. In some examples, the axis is substantially vertical. The housing may have an interior space that includes various components such as a transmit block that includes the plurality of light sources, a receive block that includes the plurality of detectors, a shared space where emitted light traverses from the transmit block to the transmit/receive lens and reflected light traverses from the transmit/receive lens to the receive block, and the transmit/receive lens that collimates the emitted light and focuses the reflected light. By rotating the housing that includes the various components, in some examples, a three-dimensional map of a 360-degree field of view of an environment of the LIDAR device can be determined without frequent recalibration of the arrangement of the various components.

In some examples, the housing may include radio frequency (RF) and optical shielding between the transmit block and the receive block. For example, the housing can be formed from and/or coated by a metal, metallic ink, or metallic foam to provide the RF shielding. Metals used for shielding can include, for example, copper or nickel.

The plurality of light sources included in the transmit block can include, for example, laser diodes. In one example, the light sources emit light with wavelengths of approximately 905 nm. In some examples, a transmit path through which the transmit/receive lens receives the light emitted by the light sources may include a reflective element, such as a mirror or prism. By including the reflective element, the transmit path can be folded to provide a smaller size of the transmit block and, hence, a smaller housing of the LIDAR device. Additionally, the transmit path includes an exit aperture of the transmit block through which the emitted light enters the shared space and traverses to the transmit/receive lens.

In some examples, each light source of the plurality of light sources includes a respective lens, such as a cylindrical or acylindrical lens. The light source may emit an uncollimated light beam that diverges more in a first direction than in a second direction. In these examples, the light source's respective lens may pre-collimate the uncollimated light beam in the first direction to provide a partially collimated light beam, thereby reducing the divergence in the first direction. In some examples, the partially collimated light beam diverges less in the first direction than in the second direction. The transmit/receive lens receives the partially collimated light beams from the one or more light sources via an exit aperture of the transmit block and the transmit/receive lens collimates the partially collimated light beams to provide collimated light beams that are transmitted into the environment of the LIDAR device. In this example, the light emitted by the light sources may have a greater divergence in the second direction than in the first direction, and the exit aperture can accommodate vertical and horizontal extents of the beams of light from the light sources.

The housing mounts the transmit/receive lens through which light from the plurality of light sources can exit the housing, and reflected light can enter the housing to reach the receive block. The transmit/receive lens can have an optical power that is sufficient to collimate the light emitted by the plurality of light sources and to focus the reflected light onto the plurality of detectors in the receive block. In one example, the transmit/receive lens has a surface with an aspheric shape that is at the outside of the housing, a surface with a toroidal shape that is inside the housing, and a focal length of approximately 120 mm.

The plurality of detectors included in the receive block can include, for example, avalanche photodiodes in a sealed environment that is filled with an inert gas, such as nitrogen. The receive block can include an entrance aperture through which focused light from the transmit/receive lens traverses towards the detectors. In some examples, the entrance aperture can include a filtering window that passes light having wavelengths within the wavelength range emitted by the plurality of light sources and attenuates light having other wavelengths.

The collimated light transmitted from the LIDAR device into the environment may reflect from one or more objects in the environment to provide object-reflected light. The transmit/receive lens may collect the object-reflected light and focus the object-reflected light through a focusing path ("receive path") onto the plurality of detectors. In some examples, the receive path may include a reflective surface that directs the focused light to the plurality of detectors. Additionally or alternatively, the reflective surface can fold the focused light towards the receive block and thus provide space savings for the shared space and the housing of the LIDAR device.

In some examples, the reflective surface may define a wall that includes the exit aperture between the transmit block and the shared space. In this case, the exit aperture of the transmit block corresponds to a transparent and/or non-reflective portion of the reflective surface. The transparent portion can be a hole or cut-away portion of the reflective surface. Alternatively, the reflective surface can be formed by forming a layer of reflective material on a transparent substrate (e.g., glass) and the transparent portion can be a portion of the substrate that is not coated with the reflective material. Thus, the shared space can be used for both the transmit path and the receive path. In some examples, the transmit path at least partially overlaps the receive path in the shared space.

The vertical and horizontal extents of the exit aperture are sufficient to accommodate the beam widths of the emitted light beams from the light sources. However, the non-reflective nature of the exit aperture prevents a portion of the collected and focused light in the receive path from reflecting, at the reflective surface, towards the detectors in the receive block. Thus, reducing the beam widths of the emitted light beams from the transmit blocks is desirable to minimize the size of the exit aperture and reduce the lost portion of the collected light. In some examples noted above, the reduction of the beam widths traversing through the exit aperture can be achieved by partially collimating the emitted light beams by including a respective lens, such as a cylindrical or acylindrical lens, adjacent to each light source.

Additionally or alternatively, to reduce the beam widths of the emitted light beams, in some examples, the transmit/receive lens can be configured to define a focal surface that has a substantial curvature in a vertical plane and/or a hori-

zontal plane. For example, the transmit/receive lens can be configured to have the aspheric surface and the toroidal surface described above that provides the curved focal surface along the vertical plane and/or the horizontal plane. In this configuration, the light sources in the transmit block can be arranged along the transmit/receive lens' curved focal surface in the transmit block, and the detectors in the receive block can be arranged on the transmit/receive lens' curved focal surface in the receive block. Thus, the emitted light beams from the light sources arranged along the curved focal surface can converge into the exit aperture having a smaller size than an aperture for light beams that are substantially parallel and/or diverging.

To facilitate such curved arrangement of the light sources, in some examples, the light sources can be mounted on a curved edge of one or more vertically-oriented printed circuit boards (PCBs), such that the curved edge of the PCB substantially matches the curvature of the focal surface in the vertical plane of the PCB. In this example, the one or more PCBs can be mounted in the transmit block along a horizontal curvature that substantially matches the curvature of the focal surface in the horizontal plane of the one or more PCBs. For example, the transmit block can include four PCBs, with each PCB mounting sixteen light sources, so as to provide 64 light sources along the curved focal plane of the transmit/receive lens in the transmit block. In this example, the 64 light sources are arranged in a pattern substantially corresponding to the curved focal surface defined by the transmit/receive lens such that the emitted light beams converge towards the exit aperture of the transmit block.

For the receive block, in some examples, the plurality of detectors can be disposed on a flexible PCB that is mounted to the receive block to conform with the shape of the transmit/receive lens' focal surface. For example, the flexible PCB may be held between two clamping pieces that have surfaces corresponding to the shape of the focal surface. Additionally, in this example, each of the plurality of detectors can be arranged on the flexible PCB so as to receive focused light from the transmit/receive lens that corresponds to a respective light source of the plurality of light sources. In this example, the detectors can be arranged in a pattern substantially corresponding to the curved focal surface of the transmit/receive lens in the receive block. Thus, in this example, the transmit/receive lens can be configured to focus onto each detector of the plurality of detectors a respective portion of the collected light that comprises light from the detector's corresponding light source.

Some embodiments of the present disclosure therefore provide systems and methods for a LIDAR device that uses a shared transmit/receive lens. In some examples, such LIDAR device can include the shared lens configured to provide a curved focal plane for transmitting light sources and receiving detectors such that light from the light sources passes through a small exit aperture included in a reflective surface that reflects collected light towards the detectors.

FIG. **1** is a block diagram of an example LIDAR device **100**. The LIDAR device **100** comprises a housing **110** that houses an arrangement of various components included in the LIDAR device **100** such as a transmit block **120**, a receive block **130**, a shared space **140**, and a lens **150**. The LIDAR device **100** includes the arrangement of the various components that provide emitted light beams **102** from the transmit block **120** that are collimated by the lens **150** and transmitted to an environment of the LIDAR device **100** as collimated light beams **104**, and collect reflected light **106** from one or more objects in the environment of the LIDAR device **100** by the lens **150** for focusing towards the receive block **130** as focused light **108**. The reflected light **106** comprises light from the collimated light beams **104** that was reflected by the one or more objects in the environment of the LIDAR device **100**. The emitted light beams **102** and the focused light **108** traverse in the shared space **140** also included in the housing **110**. In some examples, the emitted light beams **102** are propagating in a transmit path through the shared space **140** and the focused light **108** are propagating in a receive path through the shared space **140**. In some examples, the transmit path at least partially overlaps the receive path in the shared space **140**. The LIDAR device **100** can determine an aspect of the one or more objects (e.g., location, shape, etc.) in the environment of the LIDAR device **100** by processing the focused light **108** received by the receive block **130**. For example, the LIDAR device **100** can compare a time when pulses included in the emitted light beams **102** were emitted by the transmit block **120** with a time when corresponding pulses included in the focused light **108** were received by the receive block **130** and determine the distance between the one or more objects and the LIDAR device **100** based on the comparison.

The housing **110** included in the LIDAR device **100** can provide a platform for mounting the various components included in the LIDAR device **100**. The housing **110** can be formed from any material capable of supporting the various components of the LIDAR device **100** included in an interior space of the housing **110**. For example, the housing **110** may be formed from a structural material such as plastic or metal.

In some examples, the housing **110** can be configured for optical shielding to reduce ambient light and/or unintentional transmission of the emitted light beams **102** from the transmit block **120** to the receive block **130**. Optical shielding from ambient light of the environment of the LIDAR device **100** can be achieved by forming and/or coating the outer surface of the housing **110** with a material that blocks the ambient light from the environment. Additionally, inner surfaces of the housing **110** can include and/or be coated with the material described above to optically isolate the transmit block **120** from the receive block **130** to prevent the receive block **130** from receiving the emitted light beams **102** before the emitted light beams **102** reach the lens **150**.

In some examples, the housing **110** can be configured for electromagnetic shielding to reduce electromagnetic noise (e.g., Radio Frequency (RF) Noise, etc.) from ambient environment of the LIDAR device **110** and/or electromagnetic noise between the transmit block **120** and the receive block **130**. Electromagnetic shielding can improve quality of the emitted light beams **102** emitted by the transmit block **120** and reduce noise in signals received and/or provided by the receive block **130**. Electromagnetic shielding can be achieved by forming and/or coating the housing **110** with a material that absorbs electromagnetic radiation such as a metal, metallic ink, metallic foam, carbon foam, or any other material configured to absorb electromagnetic radiation. Metals that can be used for the electromagnetic shielding can include for example, copper or nickel.

In some examples, the housing **110** can be configured to have a substantially cylindrical shape and to rotate about an axis of the LIDAR device **100**. For example, the housing **110** can have the substantially cylindrical shape with a diameter of approximately 10 centimeters. In some examples, the axis is substantially vertical. By rotating the housing **110** that includes the various components, in some examples, a three-dimensional map of a 360 degree view of the environment of the LIDAR device **100** can be determined without frequent recalibration of the arrangement of the various components of the LIDAR device **100**. Additionally or alternatively, the

LIDAR device **100** can be configured to tilt the axis of rotation of the housing **110** to control the field of view of the LIDAR device **100**.

Although not illustrated in FIG. **1**, the LIDAR device **100** can optionally include a mounting structure for the housing **110**. The mounting structure can include a motor or other means for rotating the housing **110** about the axis of the LIDAR device **100**. Alternatively, the mounting structure can be included in a device and/or system other than the LIDAR device **100**.

In some examples, the various components of the LIDAR device **100** such as the transmit block **120**, receive block **130**, and the lens **150** can be removably mounted to the housing **110** in predetermined positions to reduce burden of calibrating the arrangement of each component and/or subcomponents included in each component. Thus, the housing **110** provides the platform for the various components of the LIDAR device **100** for ease of assembly, maintenance, calibration, and manufacture of the LIDAR device **100**.

The transmit block **120** includes a plurality of light sources **122** that can be configured to emit the plurality of emitted light beams **102** via an exit aperture **124**. In some examples, each of the plurality of emitted light beams **102** corresponds to one of the plurality of light sources **122**. The transmit block **120** can optionally include a mirror **126** along the transmit path of the emitted light beams **102** between the light sources **122** and the exit aperture **124**.

The light sources **122** can include laser diodes, light emitting diodes (LED), vertical cavity surface emitting lasers (VCSEL), organic light emitting diodes (OLED), polymer light emitting diodes (PLED), light emitting polymers (LEP), liquid crystal displays (LCD), microelectromechanical systems (MEMS), or any other device configured to selectively transmit, reflect, and/or emit light to provide the plurality of emitted light beams **102**. In some examples, the light sources **122** can be configured to emit the emitted light beams **102** in a wavelength range that can be detected by detectors **132** included in the receive block **130**. The wavelength range could, for example, be in the ultraviolet, visible, and/or infrared portions of the electromagnetic spectrum. In some examples, the wavelength range can be a narrow wavelength range, such as provided by lasers. In one example, the wavelength range includes wavelengths that are approximately 905 nm. Additionally, the light sources **122** can be configured to emit the emitted light beams **102** in the form of pulses. In some examples, the plurality of light sources **122** can be disposed on one or more substrates (e.g., printed circuit boards (PCB), flexible PCBs, etc.) and arranged to emit the plurality of light beams **102** towards the exit aperture **124**.

In some examples, the plurality of light sources **122** can be configured to emit uncollimated light beams included in the emitted light beams **102**. For example, the emitted light beams **102** can diverge in one or more directions along the transmit path due to the uncollimated light beams emitted by the plurality of light sources **122**. In some examples, vertical and horizontal extents of the emitted light beams **102** at any position along the transmit path can be based on an extent of the divergence of the uncollimated light beams emitted by the plurality of light sources **122**.

The exit aperture **124** arranged along the transmit path of the emitted light beams **102** can be configured to accommodate the vertical and horizontal extents of the plurality of light beams **102** emitted by the plurality of light sources **122** at the exit aperture **124**. It is noted that the block diagram shown in FIG. **1** is described in connection with functional modules for convenience in description. However, the functional modules in the block diagram of FIG. **1** can be physically implemented in other locations. For example, although illustrated that the exit aperture **124** is included in the transmit block **120**, the exit aperture **124** can be physically included in both the transmit block **120** and the shared space **140**. For example, the transmit block **120** and the shared space **140** can be separated by a wall that includes the exit aperture **124**. In this case, the exit aperture **124** can correspond to a transparent portion of the wall. In one example, the transparent portion can be a hole or cut-away portion of the wall. In another example, the wall can be formed from a transparent substrate (e.g., glass) coated with a non-transparent material, and the exit aperture **124** can be a portion of the substrate that is not coated with the non-transparent material.

In some examples of the LIDAR device **100**, it may be desirable to minimize size of the exit aperture **124** while accommodating the vertical and horizontal extents of the plurality of light beams **102**. For example, minimizing the size of the exit aperture **124** can improve the optical shielding of the light sources **122** described above in the functions of the housing **110**. Additionally or alternatively, the wall separating the transmit block **120** and the shared space **140** can be arranged along the receive path of the focused light **108**, and thus, the exit aperture **124** can be minimized to allow a larger portion of the focused light **108** to reach the wall. For example, the wall can be coated with a reflective material (e.g., reflective surface **142** in shared space **140**) and the receive path can include reflecting the focused light **108** by the reflective material towards the receive block **130**. In this case, minimizing the size of the exit aperture **124** can allow a larger portion of the focused light **108** to reflect off the reflective material that the wall is coated with.

To minimize the size of the exit aperture **124**, in some examples, the divergence of the emitted light beams **102** can be reduced by partially collimating the uncollimated light beams emitted by the light sources **122** to minimize the vertical and horizontal extents of the emitted light beams **102** and thus minimize the size of the exit aperture **124**. For example, each light source of the plurality of light sources **122** can include a cylindrical lens arranged adjacent to the light source. The light source may emit a corresponding uncollimated light beam that diverges more in a first direction than in a second direction. The cylindrical lens may pre-collimate the uncollimated light beam in the first direction to provide a partially collimated light beam, thereby reducing the divergence in the first direction. In some examples, the partially collimated light beam diverges less in the first direction than in the second direction. Similarly, uncollimated light beams from other light sources of the plurality of light sources **122** can have a reduced beam width in the first direction and thus the emitted light beams **102** can have a smaller divergence due to the partially collimated light beams. In this example, at least one of the vertical and horizontal extents of the exit aperture **124** can be reduced due to partially collimating the light beams **102**.

Additionally or alternatively, to minimize the size of the exit aperture **124**, in some examples, the light sources **122** can be arranged along a substantially curved surface defined by the transmit block **120**. The curved surface can be configured such that the emitted light beams **102** converge towards the exit aperture **124**, and thus the vertical and horizontal extents of the emitted light beams **102** at the exit aperture **124** can be reduced due to the arrangement of the light sources **122** along the curved surface of the transmit block **120**. In some examples, the curved surface of the transmit block **120** can include a curvature along the first direction of divergence of the emitted light beams **102** and a curvature along the second direction of divergence of the emitted light beams **102**, such

that the plurality of light beams **102** converge towards a central area in front of the plurality of light sources **122** along the transmit path.

To facilitate such curved arrangement of the light sources **122**, in some examples, the light sources **122** can be disposed on a flexible substrate (e.g., flexible PCB) having a curvature along one or more directions. For example, the curved flexible substrate can be curved along the first direction of divergence of the emitted light beams **102** and the second direction of divergence of the emitted light beams **102**. Additionally or alternatively, to facilitate such curved arrangement of the light sources **122**, in some examples, the light sources **122** can be disposed on a curved edge of one or more vertically-oriented printed circuit boards (PCBs), such that the curved edge of the PCB substantially matches the curvature of the first direction (e.g., the vertical plane of the PCB). In this example, the one or more PCBs can be mounted in the transmit block **120** along a horizontal curvature that substantially matches the curvature of the second direction (e.g., the horizontal plane of the one or more PCBs). For example, the transmit block **120** can include four PCBs, with each PCB mounting sixteen light sources, so as to provide 64 light sources along the curved surface of the transmit block **120**. In this example, the 64 light sources are arranged in a pattern such that the emitted light beams **102** converge towards the exit aperture **124** of the transmit block **120**.

The transmit block **120** can optionally include the mirror **126** along the transmit path of the emitted light beams **102** between the light sources **122** and the exit aperture **124**. By including the mirror **126** in the transmit block **120**, the transmit path of the emitted light beams **102** can be folded to provide a smaller size of the transmit block **120** and the housing **110** of the LIDAR device **100** than a size of another transmit block where the transmit path that is not folded.

The receive block **130** includes a plurality of detectors **132** that can be configured to receive the focused light **108** via an entrance aperture **134**. In some examples, each of the plurality of detectors **132** is configured and arranged to receive a portion of the focused light **108** corresponding to a light beam emitted by a corresponding light source of the plurality of light sources **122** and reflected of the one or more objects in the environment of the LIDAR device **100**. The receive block **130** can optionally include the detectors **132** in a sealed environment having an inert gas **136**.

The detectors **132** may comprise photodiodes, avalanche photodiodes, phototransistors, cameras, active pixel sensors (APS), charge coupled devices (CCD), cryogenic detectors, or any other sensor of light configured to receive focused light **108** having wavelengths in the wavelength range of the emitted light beams **102**.

To facilitate receiving, by each of the detectors **132**, the portion of the focused light **108** from the corresponding light source of the plurality of light sources **122**, the detectors **132** can be disposed on one or more substrates and arranged accordingly. For example, the light sources **122** can be arranged along a curved surface of the transmit block **120**, and the detectors **132** can also be arranged along a curved surface of the receive block **130**. The curved surface of the receive block **130** can similarly be curved along one or more axes of the curved surface of the receive block **130**. Thus, each of the detectors **132** are configured to receive light that was originally emitted by a corresponding light source of the plurality of light sources **122**.

To provide the curved surface of the receive block **130**, the detectors **132** can be disposed on the one or more substrates similarly to the light sources **122** disposed in the transmit block **120**. For example, the detectors **132** can be disposed on a flexible substrate (e.g., flexible PCB) and arranged along the curved surface of the flexible substrate to each receive focused light originating from a corresponding light source of the light sources **122**. In this example, the flexible substrate may be held between two clamping pieces that have surfaces corresponding to the shape of the curved surface of the receive block **130**. Thus, in this example, assembly of the receive block **130** can be simplified by sliding the flexible substrate onto the receive block **130** and using the two clamping pieces to hold it at the correct curvature.

The focused light **108** traversing along the receive path can be received by the detectors **132** via the entrance aperture **134**. In some examples, the entrance aperture **134** can include a filtering window that passes light having wavelengths within the wavelength range emitted by the plurality of light sources **122** and attenuates light having other wavelengths. In this example, the detectors **132** receive the focused light **108** substantially comprising light having the wavelengths within the wavelength range.

In some examples, the plurality of detectors **132** included in the receive block **130** can include, for example, avalanche photodiodes in a sealed environment that is filled with the inert gas **136**. The inert gas **136** may comprise, for example, nitrogen.

The shared space **140** includes the transmit path for the emitted light beams **102** from the transmit block **120** to the lens **150**, and includes the receive path for the focused light **108** from the lens **150** to the receive block **130**. In some examples, the transmit path at least partially overlaps with the receive path in the shared space **140**. By including the transmit path and the receive path in the shared space **140**, advantages with respect to size, cost, and/or complexity of assembly, manufacture, and/or maintenance of the LIDAR device **100** can be provided.

In some examples, the shared space **140** can include a reflective surface **142**. The reflective surface **142** can be arranged along the receive path and configured to reflect the focused light **108** towards the entrance aperture **134** and onto the detectors **132**. The reflective surface **142** may comprise a prism, mirror or any other optical element configured to reflect the focused light **108** towards the entrance aperture **134** in the receive block **130**. In some examples where a wall separates the shared space **140** from the transmit block **120**. In these examples, the wall may comprise a transparent substrate (e.g., glass) and the reflective surface **142** may comprise a reflective coating on the wall with an uncoated portion for the exit aperture **124**.

In embodiments including the reflective surface **142**, the reflective surface **142** can reduce size of the shared space **140** by folding the receive path similarly to the mirror **126** in the transmit block **120**. Additionally or alternatively, in some examples, the reflective surface **142** can direct the focused light **103** to the receive block **130** further providing flexibility to the placement of the receive block **130** in the housing **110**. For example, varying the tilt of the reflective surface **142** can cause the focused light **108** to be reflected to various portions of the interior space of the housing **110**, and thus the receive block **130** can be placed in a corresponding position in the housing **110**. Additionally or alternatively, in this example, the LIDAR device **100** can be calibrated by varying the tilt of the reflective surface **142**.

The lens **150** mounted to the housing **110** can have an optical power to both collimate the emitted light beams **102** from the light sources **122** in the transmit block **120**, and focus the reflected light **106** from the one or more objects in the environment of the LIDAR device **100** onto the detectors **132** in the receive block **130**. In one example, the lens **150** has

a focal length of approximately 120 mm. By using the same lens **150** to perform both of these functions, instead of a transmit lens for collimating and a receive lens for focusing, advantages with respect to size, cost, and/or complexity can be provided. In some examples, collimating the emitted light beams **102** to provide the collimated light beams **104** allows determining the distance travelled by the collimated light beams **104** to the one or more objects in the environment of the LIDAR device **100**.

In an example scenario, the emitted light beams **102** from the light sources **122** traversing along the transmit path can be collimated by the lens **150** to provide the collimated light beams **104** to the environment of the LIDAR device **100**. The collimated light beams **104** may then reflect off the one or more objects in the environment of the LIDAR device **100** and return to the lens **150** as the reflected light **106**. The lens **150** may then collect and focus the reflected light **106** as the focused light **108** onto the detectors **132** included in the receive block **130**. In some examples, aspects of the one or more objects in the environment of the LIDAR device **100** can be determined by comparing the emitted light beams **102** with the focused light beams **108**. The aspects can include, for example, distance, shape, color, and/or material of the one or more objects. Additionally, in some examples, rotating the housing **110**, a three dimensional map of the surroundings of the LIDAR device **100** can be determined.

In some examples where the plurality of light sources **122** are arranged along the curved surface of the transmit block **120**, the lens **150** can be configured to have a focal surface corresponding to the curved surface of the transmit block **120**. For example, the lens **150** can include an aspheric surface outside the housing **110** and a toroidal surface inside the housing **110** facing the shared space **140**. In this example, the shape of the lens **150** allows the lens **150** to both collimate the emitted light beams **102** and focus the reflected light **106**. Additionally, in this example, the shape of the lens **150** allows the lens **150** to have the focal surface corresponding to the curved surface of the transmit block **120**. In some examples, the focal surface provided by the lens **150** substantially matches the curved shape of the transmit block **120**. Additionally, in some examples, the detectors **132** can be arranged similarly in the curved shape of the receive block **130** to receive the focused light **108** along the curved focal surface provided by the lens **150**. Thus, in some examples, the curved surface of the receive block **130** may also substantially match the curved focal surface provided by the lens **150**.

FIG. **2** is a cross-section view of an example LIDAR device **200**. In this example, the LIDAR device **200** includes a housing **210** that houses a transmit block **220**, a receive block **230**, a shared space **240**, and a lens **250**. For purposes of illustration, FIG. **2** shows an x-y-z axis, in which the z-axis is in a substantially vertical direction and the x-axis and y-axis define a substantially horizontal plane.

The structure, function, and operation of various components included in the LIDAR device **200** are similar to corresponding components included in the LIDAR device **100** described in FIG. **1**. For example, the housing **210**, the transmit block **220**, the receive block **230**, the shared space **240**, and the lens **250** are similar, respectively, to the housing **110**, the transmit block **120**, the receive block **130**, and the shared space **140** described in FIG. **1**.

The transmit block **220** includes a plurality of light sources **222***a-c* arranged along a curved focal surface **228** defined by the lens **250**. The plurality of light sources **222***a-c* can be configured to emit, respectively, the plurality of light beams **202***a-c* having wavelengths within a wavelength range. For example, the plurality of light sources **222***a-c* may comprise laser diodes that emit the plurality of light beams **202***a-c* having the wavelengths within the wavelength range. The plurality of light beams **202***a-c* are reflected by mirror **224** through an exit aperture **226** into the shared space **240** and towards the lens **250**. The structure, function, and operation of the plurality of light sources **222***a-c*, the mirror **224**, and the exit aperture **226** can be similar, respectively, to the plurality of light sources **122**, the mirror **124**, and the exit aperture **226** discussed in the description of the LIDAR device **100** of FIG. **1**.

Although FIG. **2** shows that the curved focal surface **228** is curved in the x-y plane (horizontal plane), additionally or alternatively, the plurality of light sources **222***a-c* may be arranged along a focal surface that is curved in a vertical plane. For example, the curved focal surface **228** can have a curvature in a vertical plane, and the plurality of light sources **222***a-c* can include additional light sources arranged vertically along the curved focal surface **228** and configured to emit light beams directed at the mirror **224** and reflected through the exit aperture **226**.

Due to the arrangement of the plurality of light sources **222***a-c* along the curved focal surface **228**, the plurality of light beams **202***a-c*, in some examples, may converge towards the exit aperture **226**. Thus, in these examples, the exit aperture **226** may be minimally sized while being capable of accommodating vertical and horizontal extents of the plurality of light beams **202***a-c*. Additionally, in some examples, the curved focal surface **228** can be defined by the lens **250**. For example, the curved focal surface **228** may correspond to a focal surface of the lens **250** due to shape and composition of the lens **250**. In this example, the plurality of light sources **222***a-c* can be arranged along the focal surface defined by the lens **250** at the transmit block.

The plurality of light beams **202***a-c* propagate in a transmit path that extends through the transmit block **220**, the exit aperture **226**, and the shared space **240** towards the lens **250**. The lens **250** collimates the plurality of light beams **202***a-c* to provide collimated light beams **204***a-c* into an environment of the LIDAR device **200**. The collimated light beams **204***a-c* correspond, respectively, to the plurality of light beams **202***a-c*. In some examples, the collimated light beams **204***a-c* reflect off one or more objects in the environment of the LIDAR device **200** as reflected light **206**. The reflected light **206** may be focused by the lens **250** into the shared space **240** as focused light **208** traveling along a receive path that extends through the shared space **240** onto the receive block **230**. For example, the focused light **208** may be reflected by the reflective surface **242** as focused light **208***a-c* propagating towards the receive block **230**.

The lens **250** may be capable of both collimating the plurality of light beams **202***a-c* and focusing the reflected light **206** along the receive path **208** towards the receive block **230** due to shape and composition of the lens **250**. For example, the lens **250** can have an aspheric surface **252** facing outside of the housing **210** and a toroidal surface **254** facing the shared space **240**. By using the same lens **250** to perform both of these functions, instead of a transmit lens for collimating and a receive lens for focusing, advantages with respect to size, cost, and/or complexity can be provided.

The exit aperture **226** is included in a wall **244** that separates the transmit block **220** from the shared space **240**. In some examples, the wall **244** can be formed from a transparent material (e.g., glass) that is coated with a reflective material **242**. In this example, the exit aperture **226** may correspond to the portion of the wall **244** that is not coated by the reflective material **242**. Additionally or alternatively, the exit aperture **226** may comprise a hole or cut-away in the wall **244**.

The focused light **208** is reflected by the reflective surface **242** and directed towards an entrance aperture **234** of the receive block **230**. In some examples, the entrance aperture **234** may comprise a filtering window configured to allow wavelengths in the wavelength range of the plurality of light beams **202***a-c* emitted by the plurality of light sources **222***a-c* and attenuate other wavelengths. The focused light **208***a-c* reflected by the reflective surface **242** from the focused light **208** propagates, respectively, onto a plurality of detectors **232***a-c*. The structure, function, and operation of the entrance aperture **234** and the plurality of detectors **232***a-c* is similar, respectively, to the entrance aperture **134** and the plurality of detectors **132** included in the LIDAR device **100** described in FIG. **1**.

The plurality of detectors **232***a-c* can be arranged along a curved focal surface **238** of the receive block **230**. Although FIG. **2** shows that the curved focal surface **238** is curved along the x-y plane (horizontal plane), additionally or alternatively, the curved focal surface **238** can be curved in a vertical plane. The curvature of the focal surface **238** is also defined by the lens **250**. For example, the curved focal surface **238** may correspond to a focal surface of the light projected by the lens **250** along the receive path at the receive block **230**.

Each of the focused light **208***a-c* corresponds, respectively, to the emitted light beams **202***a-c* and is directed onto, respectively, the plurality of detectors **232***a-c*. For example, the detector **232***a* is configured and arranged to received focused light **208***a* that corresponds to collimated light beam **204***a* reflected of the one or more objects in the environment of the LIDAR device **200**. In this example, the collimated light beam **204***a* corresponds to the light beam **202***a* emitted by the light source **222***a*. Thus, the detector **232***a* receives light that was emitted by the light source **222***a*, the detector **232***b* receives light that was emitted by the light source **222***b*, and the detector **232***c* receives light that was emitted by the light source **222***c*.

By comparing the received light **208***a-c* with the emitted light beams **202***a-c*, at least one aspect of the one or more object in the environment of the LIDAR device **200** may be determined. For example, by comparing a time when the plurality of light beams **202***a-c* were emitted by the plurality of light sources **222***a-c* and a time when the plurality of detectors **232***a-c* received the focused light **208***a-c*, a distance between the LIDAR device **200** and the one or more object in the environment of the LIDAR device **200** may be determined. In some examples, other aspects such as shape, color, material, etc. may also be determined.

In some examples, the LIDAR device **200** may be rotated about an axis to determine a three-dimensional map of the surroundings of the LIDAR device **200**. For example, the LIDAR device **200** may be rotated about a substantially vertical axis as illustrated by arrow **290**. Although illustrated that the LIDAR device **200** is rotated counter clock-wise about the axis as illustrated by the arrow **290**, additionally or alternatively, the LIDAR device **200** may be rotated in the clockwise direction. In some examples, the LIDAR device **200** may be rotated 360 degrees about the axis. In other examples, the LIDAR device **200** may be rotated back and forth along a portion of the 360 degree view of the LIDAR device **200**. For example, the LIDAR device **200** may be mounted on a platform that wobbles back and forth about the axis without making a complete rotation.

FIG. **3**A is a perspective view of an example LIDAR device **300** fitted with various components, in accordance with at least some embodiments described herein. FIG. **3**B is a perspective view of the example LIDAR device **300** shown in FIG. **3**A with the various components removed to illustrate interior space of the housing **310**. The structure, function, and operation of the LIDAR device **300** is similar to the LIDAR devices **100** and **200** described, respectively, in FIGS. **1** and **2**. For example, the LIDAR device **300** includes a housing **310** that houses a transmit block **320**, a receive block **330**, and a lens **350** that are similar, respectively, to the housing **110**, the transmit block **120**, the receive block **130**, and the lens **150** described in FIG. **1**. Additionally, collimated light beams **304** propagate from the lens **350** toward an environment of the LIDAR device **300** and reflect of one or more objects in the environment as reflected light **306**, similarly to the collimated light beams **104** and reflected light **106** described in FIG. **1**.

The LIDAR device **300** can be mounted on a mounting structure **360** and rotated about an axis to provide a 360 degree view of the environment surrounding the LIDAR device **300**. In some examples, the mounting structure **360** may comprise a movable platform that may tilt in one or more directions to change the axis of rotation of the LIDAR device **300**.

As illustrated in FIG. **3**B, the various components of the LIDAR device **300** can be removably mounted to the housing **310**. For example, the transmit block **320** may comprise one or more printed circuit boards (PCBs) that are fitted in the portion of the housing **310** where the transmit block **320** can be mounted. Additionally, the receive block **330** may comprise a plurality of detectors **332** mounted to a flexible substrate and can be removably mounted to the housing **310** as a block that includes the plurality of detectors. Similarly, the lens **350** can be mounted to another side of the housing **310**.

A plurality of light beams **302** can be transmitted by the transmit block **320** into the shared space **340** and towards the lens **350** to be collimated into the collimated light beams **304**. Similarly, the received light **306** can be focused by the lens **350** and directed through the shared space **340** onto the receive block **330**.

FIG. **4** illustrates an example transmit block **420**, in accordance with at least some embodiments described herein. Transmit block **420** can correspond to the transmit blocks **120**, **220**, and **320** described in FIGS. **1-3**. For example, the transmit block **420** includes a plurality of light sources **422***a-c* similar to the plurality of light sources **222***a-c* included in the transmit block **220** of FIG. **2**. Additionally, the light sources **422***a-c* are arranged along a focal surface **428**, which is curved in a vertical plane. The light sources **422***a-c* are configured to emit a plurality of light beams **402***a-c* that converge and propagate through an exit aperture **426** in a wall **444**.

Although the plurality of light sources **422***a-c* can be arranged along a focal surface **428** that is curved in a vertical plane, additionally or alternatively, the plurality of light sources **422***a-c* can be arranged along a focal surface that is curved in a horizontal plane or a focal surface that is curved both vertically and horizontally. For example, the plurality of light sources **422***a-c* can be arranged in a curved three dimensional grid pattern. For example, the transmit block **420** may comprise a plurality of printed circuit board (PCB) vertically mounted such that a column of light sources such as the plurality of light sources **422***a-c* are along the vertical axis of each PCB and each of the plurality of PCBs can be arranged adjacent to other vertically mounted PCBs along a horizontally curved plane to provide the three dimensional grid pattern.

As shown in FIG. **4**, the light beams **402***a-c* converge towards the exit aperture **426** which allows the size of the exit aperture **426** to be minimized while accommodating vertical and horizontal extents of the light beams **402***a-c* similarly to the exit aperture **226** described in FIG. **2**.

As noted above in the description of FIG. **1**, the light from light sources **122** could be partially collimated to fit through the exit aperture **124**. FIGS. **5**A, **5**B, and **5**C illustrate an example of how such partial collimation could be achieved. In this example, a light source **500** is made up of a laser diode **502** and a cylindrical lens **504**. As shown in FIG. **5**A, laser diode **502** has an aperture **506** with a shorter dimension corresponding to a fast axis **508** and a longer dimension corresponding to a slow axis **510**. FIGS. **5**B and **5**C show an uncollimated laser beam **512** being emitted from laser diode **502**. Laser beam **512** diverges in two directions, one direction defined by fast axis **508** and another, generally orthogonal direction defined by slow axis **510**. FIG. **5**B shows the divergence of laser beam **512** along fast axis **508**, whereas FIG. **5**C shows the divergence of laser beam **512** along slow axis **510**. Laser beam **512** diverges more quickly along fast axis **508** than along slow axis **510**.

In one specific example, laser diode **502** is an Osram SPL DL90_3 nanostack pulsed laser diode that emits pulses of light with a range of wavelengths from about 896 nm to about 910 nm (a nominal wavelength of 905 nm). In this specific example, the aperture has a shorter dimension of about 10 microns, corresponding to its fast axis, and a longer dimension of about 200 microns, corresponding to its slow axis. The divergence of the laser beam in this specific example is about 25 degrees along the fast axis and about 11 degrees along the slow axis. It is to be understood that this specific example is illustrative only. Laser diode **502** could have a different configuration, different aperture sizes, different beam divergences, and/or emit different wavelengths.

As shown in FIGS. **5**B and **5**C, cylindrical lens **504** may be positioned in front of aperture **506** with its cylinder axis **514** generally parallel to slow axis **510** and perpendicular to fast axis **508**. In this arrangement, cylindrical lens **504** can pre-collimate laser beam **512** along fast axis **508**, resulting in partially collimated laser beam **516**. In some examples, this pre-collimation may reduce the divergence along fast axis **508** to about one degree or less. Nonetheless, laser beam **516** is only partially collimated because the divergence along slow axis **510** may be largely unchanged by cylindrical lens **504**. Thus, whereas uncollimated laser beam **512** emitted by laser diode has a higher divergence along fast axis **508** than along slow axis **510**, partially collimated laser beam **516** provided by cylindrical lens **504** may have a higher divergence along slow axis **510** than along fast axis **508**. Further, the divergences along slow axis **510** in uncollimated laser beam **512** and in partially collimated laser beam **516** may be substantially equal.

In one example, cylindrical lens **504** is a microrod lens with a diameter of about 600 microns that is placed about 250 microns in front of aperture **506**. The material of the microrod lens could be, for example, fused silica or a borosilicate crown glass, such as Schott BK7. Alternatively, the microrod lens could be a molded plastic cylinder or acylinder. Cylindrical lens **504** could also be used to provide magnification along fast axis **508**. For example, if the dimensions of aperture **506** are 10 microns by 200 microns, as previously described, and cylindrical lens **504** is a microrod lens as described above, then cylindrical lens **504** may magnify the shorter dimension (corresponding to fast axis **508**) by about 20 times. This magnification effectively stretches out the shorter dimension of aperture **506** to about the same as the longer dimension. As a result, when light from laser beam **516** is focused, for example, focused onto a detector, the focused spot could have a substantially square shape instead of the rectangular slit shape of aperture **506**.

FIG. **6**A illustrates an example receive block **630**, in accordance with at least some embodiments described herein. FIG. **6**B illustrates a side view of three detectors **632***a-c* included in the receive block **630** of FIG. **6**A. Receive block **630** can correspond to the receive blocks **130**, **230**, and **330** described in FIGS. **1-3**. For example, the receive block **630** includes a plurality of detectors **632***a-c* arranged along a curved surface **638** defined by a lens **650** similarly to the receive block **230**, the detectors **232** and the curved plane **238** described in FIG. **2**. Focused light **608***a-c* from lens **650** propagates along a receive path that includes a reflective surface **642** onto the detectors **632***a-c* similar, respectively, to the focused light **208***a-c*, the lens **250**, the reflective surface **242**, and the detectors **232***a-c* described in FIG. **2**.

The receive block **630** comprises a flexible substrate **680** on which the plurality of detectors **632***a-c* are arranged along the curved surface **638**. The flexible substrate **680** conforms to the curved surface **638** by being mounted to a receive block housing **690** having the curved surface **638**. As illustrated in FIG. **6**, the curved surface **638** includes the arrangement of the detectors **632***a-c* curved along a vertical and horizontal axis of the receive block **630**.

FIGS. **7**A and **7**B illustrate an example lens **750** with an aspheric surface **752** and a toroidal surface **754**, in accordance with at least some embodiments described herein. FIG. **7**B illustrates a cross-section view of the example lens **750** shown in FIG. **7**A. The lens **750** can correspond to lens **150**, **250**, and **350** included in FIGS. **1-3**. For example, the lens **750** can be configured to both collimate light incident on the toroidal surface **754** from a light source into collimated light propagating out of the aspheric surface **752**, and focus reflected light entering from the aspheric surface **752** onto a detector. The structure of the lens **750** including the aspheric surface **752** and the toroidal surface **754** allows the lens **750** to perform both functions of collimating and focusing described in the example above.

In some examples, the lens **750** defines a focal surface of the light propagating through the lens **750** due to the aspheric surface **752** and the toroidal surface **754**. In these examples, the light sources providing the light entering the toroidal surface **754** can be arranged along the defined focal surface, and the detectors receiving the light focused from the light entering the aspheric surface **752** can also be arranged along the defined focal surface.

By using the lens **750** that performs both of these functions (collimating transmitted light and focusing received light), instead of a transmit lens for collimating and a receive lens for focusing, advantages with respect to size, cost, and/or complexity can be provided.

FIG. **8**A illustrates an example LIDAR device **810** mounted on a vehicle **800**, in accordance with at least some embodiments described herein. FIG. **8**A shows a Right Side View, Front View, Back View, and Top View of the vehicle **800**. Although vehicle **800** is illustrated in FIG. **8** as a car, other examples are possible. For instance, the vehicle **800** could represent a truck, a van, a semi-trailer truck, a motorcycle, a golf cart, an off-road vehicle, or a farm vehicle, among other examples.

The structure, function, and operation of the LIDAR device **810** shown in FIG. **8**A is similar to the example LIDAR devices **100**, **200**, and **300** shown in FIGS. **1-3**. For example, the LIDAR device **810** can be configured to rotate about an axis and determine a three-dimensional map of a surrounding environment of the LIDAR device **810**. To facilitate the rotation, the LIDAR device **810** can be mounted on a platform **802**. In some examples, the platform **802** may comprise a

movable mount that allows the vehicle **800** to control the axis of rotation of the LIDAR device **810**.

While the LIDAR device **810** is shown to be mounted in a particular location on the vehicle **800**, in some examples, the LIDAR device **810** may be mounted elsewhere on the vehicle **800**. For example, the LIDAR device **810** may be mounted anywhere on top of the vehicle **800**, on a side of the vehicle **800**, under the vehicle **800**, on a hood of the vehicle **800**, and/or on a trunk of the vehicle **800**.

The LIDAR device **810** includes a lens **812** through which collimated light is transmitted from the LIDAR device **810** to the surrounding environment of the LIDAR device **810**, similarly to the lens **150**, **250**, and **350** described in FIGS. **1-3**. Similarly, the lens **812** can also be configured to receive reflected light from the surrounding environment of the LIDAR device **810** that were reflected off one or more objects in the surrounding environment.

FIG. **8**B illustrates a scenario where the LIDAR device **810** shown in FIG. **8**A and scanning an environment **830** that includes one or more objects, in accordance with at least some embodiments described herein. In this example scenario, vehicle **800** can be traveling on a road **822** in the environment **830**. By rotating the LIDAR device **810** about the axis defined by the platform **802**, the LIDAR device **810** may be able to determine aspects of objects in the surrounding environment **830**, such as lane lines **824***a-b*, other vehicles **826***a-c*, and/or street sign **828**. Thus, the LIDAR device **810** can provide the vehicle **800** with information about the objects in the surrounding environment **830**, including distance, shape, color, and/or material type of the objects.

FIG. **9** is a flowchart of a method **900** of operating a LIDAR device, in accordance with at least some embodiments described herein. Method **900** shown in FIG. **9** presents an embodiment of a method that could be used with the LIDAR devices **100**, **200**, and **300**, for example. Method **900** may include one or more operations, functions, or actions as illustrated by one or more of blocks **902-912**. Although the blocks are illustrated in a sequential order, these blocks may in some instances be performed in parallel, and/or in a different order than those described herein. Also, the various blocks may be combined into fewer blocks, divided into additional blocks, and/or removed based upon the desired implementation.

In addition, for the method **900** and other processes and methods disclosed herein, the flowchart shows functionality and operation of one possible implementation of present embodiments. In this regard, each block may represent a module, a segment, or a portion of a manufacturing or operation process.

At block **902**, the method **900** includes rotating a housing of a light detection and ranging (LIDAR) device about an axis, wherein the housing has an interior space that includes a transmit block, a receive block, and a shared space, wherein the transmit block has an exit aperture, and wherein the receive block has an entrance aperture.

At block **904**, the method **900** includes emitting, by a plurality of light sources in the transmit block, a plurality of light beams that enter the shared space via a transmit path, the light beams comprising light having wavelengths in a wavelength range.

At block **906**, the method **900** includes receiving the light beams at a lens mounted to the housing along the transmit path.

At block **908**, the method **900** includes collimating, by the lens, the light beams for transmission into an environment of the LIDAR device.

At block **910**, the method **900** includes focusing, by the lens, the collected light onto a plurality of detectors in the receive block via a receive path that extends through the shared space and the entrance aperture of the receive block.

At block **912**, the method **900** includes detecting, by the plurality of detectors in the receive block, light from the focused light having wavelengths in the wavelength range.

For example, a LIDAR device such as the LIDAR device **200** can be rotated about an axis (block **902**). A transmit block, such as the transmit block **220**, can include a plurality of light sources that emit light beams having wavelengths in a wavelength range, through an exit aperture and a shared space to a lens (block **904**). The light beams can be received by the lens (block **906**) and collimated for transmission to an environment of the LIDAR device (block **908**). The collimated light may then reflect off one or more objects in the environment of the LIDAR device and return as reflected light collected by the lens. The lens may then focus the collected light onto a plurality of detectors in the receive block via a receive path that extends through the shared space and an entrance aperture of the receive block (block **910**). The plurality of detectors in the receive block may then detect light from the focused light having wavelengths in the wavelength range of the emitted light beams from the light sources (block **912**).

Within examples, devices and operation methods described include a LIDAR device rotated about an axis and configured to transmit collimated light and focus reflected light. The collimation and focusing can be performed by a shared lens. By using a shared lens that performs both of these functions, instead of a transmit lens for collimating and a receive lens for focusing, advantages with respect to size, cost, and/or complexity can be provided. Additionally, in some examples, the shared lens can define a curved focal surface. In these examples, the light sources emitting light through the shared lens and the detectors receiving light focused by the shared lens can be arranged along the curved focal surface defined by the shared lens.

It should be understood that arrangements described herein are for purposes of example only. As such, those skilled in the art will appreciate that other arrangements and other elements (e.g. machines, interfaces, functions, orders, and groupings of functions, etc.) can be used instead, and some elements may be omitted altogether according to the desired results. Further, many of the elements that are described are functional entities that may be implemented as discrete or distributed components or in conjunction with other components, in any suitable combination and location, or other structural elements described as independent structures may be combined.

While various aspects and embodiments have been disclosed herein, other aspects and embodiments will be apparent to those skilled in the art. The various aspects and embodiments disclosed herein are for purposes of illustration and are not intended to be limiting, with the true scope being indicated by the following claims, along with the full scope of equivalents to which such claims are entitled. It is also to be understood that the terminology used herein is for the purpose of describing particular embodiments only, and is not intended to be limiting.

What is claimed is:

1. A light detection and ranging (LIDAR) device, comprising:

a lens mounted to a housing, wherein the housing is configured to rotate about an axis and has an interior space that includes a transmit block, a receive block, a transmit path, and a receive path, wherein the transmit block has an exit aperture in a wall that comprises a reflective surface, wherein the receive block has an entrance aperture, wherein the transmit path extends from the exit

aperture to the lens, and wherein the receive path extends from the lens to the entrance aperture via the reflective surface;

a plurality of light sources in the transmit block, wherein the plurality of light sources are configured to emit a plurality of light beams through the exit aperture in a plurality of different directions, the light beams comprising light having wavelengths in a wavelength range;

a plurality of detectors in the receive block, wherein the plurality of detectors are configured to detect light having wavelengths in the wavelength range; and

wherein the lens is configured to receive the light beams via the transmit path, collimate the light beams for transmission into an environment of the LIDAR device, collect light comprising light from one or more of the collimated light beams reflected by one or more objects in the environment of the LIDAR device, and focus the collected light onto the detectors via the receive path.

2. The LIDAR device of claim **1**, wherein each detector in the plurality of detectors is associated with a corresponding light source in the plurality of light sources, and wherein the lens is configured to focus onto each detector a respective portion of the collected light that comprises light from the detector's corresponding light source.

3. The LIDAR device of claim **1**, wherein the wall comprises a transparent material, the reflective surface covers a portion of the transparent material, and the exit aperture corresponds to a portion of the transparent material that is not covered by the reflective surface.

4. The LIDAR device of claim **1**, wherein the transmit path at least partially overlaps the receive path.

5. The LIDAR device of claim **1**, wherein the lens defines a curved focal surface in the transmit block and a curved focal surface in the receive block.

6. The LIDAR device of claim **5**, wherein the light sources in the plurality of light sources are arranged in a pattern substantially corresponding to the curved focal surface in the transmit block, and wherein the detectors in the plurality of detectors are arranged in a pattern substantially corresponding to the curved focal surface in the receive block.

7. The LIDAR device of claim **1**, wherein the lens has an aspheric surface and a toroidal surface.

8. The LIDAR device of claim **7**, wherein the toroidal surface is in the interior space within the housing and the aspheric surface is outside of the housing.

9. The LIDAR device of claim **1**, wherein the axis is substantially vertical.

10. The LIDAR device of claim **1**, further comprising a mirror in the transmit block, wherein the mirror is configured to reflect the light beams toward the exit aperture.

11. The LIDAR device of claim **1**, wherein the receive block comprises a sealed environment containing an inert gas.

12. The LIDAR device of claim **1**, wherein the entrance aperture comprises a material that passes light having wavelengths in the wavelength range and attenuates light having other wavelengths.

13. The LIDAR device of claim **1**, wherein each light source in the plurality of light sources comprises a respective laser diode.

14. The LIDAR device of claim **1**, wherein each detector in the plurality of detectors comprises a respective avalanche photodiode.

15. A method comprising:

rotating a housing of a light detection and ranging (LIDAR) device about an axis, wherein the housing mounts a lens and has an interior space that includes a transmit block, a receive block, a transmit path, and a receive path, wherein the transmit block has an exit aperture in a wall that comprises a reflective surface, wherein the receive block has an entrance aperture, wherein the transmit path extends from the exit aperture to the lens, and wherein the receive path extends from the lens to the entrance aperture via the reflective surface;

emitting, by a plurality of light sources in the transmit block, a plurality of light beams through the exit aperture in a plurality of different directions, the light beams comprising light having wavelengths in a wavelength range;

receiving, by the lens, the light beams via the transmit path;

collimating, by the lens, the light beams for transmission into an environment of the LIDAR device;

collecting, by the lens, light from one or more of the collimated light beams reflected by one or more objects in the environment of the LIDAR device;

focusing, by the lens, the collected light onto a plurality of detectors in the receive block via the receive path; and

detecting, by the plurality of detectors in the receive block, light from the focused light having wavelengths in the wavelength range.

16. The method of claim **15**, wherein each detector in the plurality of detectors is associated with a corresponding light source in the plurality of light sources, the method further comprising:

focusing onto each detector, by the lens, a respective portion of the collected light that comprises light from the detector's corresponding light source.

17. The method of claim **15**, further comprising:

reflecting, by a mirror in the transmit block, the emitted light beams toward the exit aperture.

18. The method of claim **15**, wherein the wall comprises a transparent material, the reflective surface covers a portion of the transparent material, and the exit aperture corresponds to a portion of the transparent material that is not covered by the reflective surface.

* * * * *

EXHIBIT B

US009368936B1

(12) **United States Patent**
Lenius et al.

(10) **Patent No.: US 9,368,936 B1**
(45) **Date of Patent: Jun. 14, 2016**

(54) **LASER DIODE FIRING SYSTEM**

(71) Applicant: **Google Inc.**, Mountain View, CA (US)

(72) Inventors: **Samuel William Lenius**, Sunnyvale, CA (US); **Pierre-yves Droz**, Mountain View, CA (US)

(73) Assignee: **Google Inc.**, Mountain View, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 378 days.

(21) Appl. No.: **14/132,219**

(22) Filed: **Dec. 18, 2013**

Related U.S. Application Data

(60) Provisional application No. 61/884,762, filed on Sep. 30, 2013.

(51) **Int. Cl.**

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H01S 5/06	(2006.01)
G01S 17/32	(2006.01)
H01S 5/062	(2006.01)
H05B 33/08	(2006.01)
G01J 1/46	(2006.01)

(52) **U.S. Cl.**
CPC . ***H01S 5/06*** (2013.01); ***G01S 17/32*** (2013.01); *G01J 1/46* (2013.01); *H01S 5/062* (2013.01); *H05B 33/0842* (2013.01); *H05B 33/0845* (2013.01)

(58) **Field of Classification Search**
CPC ... G01J 1/46; H05B 33/0845; H05B 33/0842; H01S 5/06; H01S 5/062; G01S 17/06
USPC 359/4.01
See application file for complete search history.

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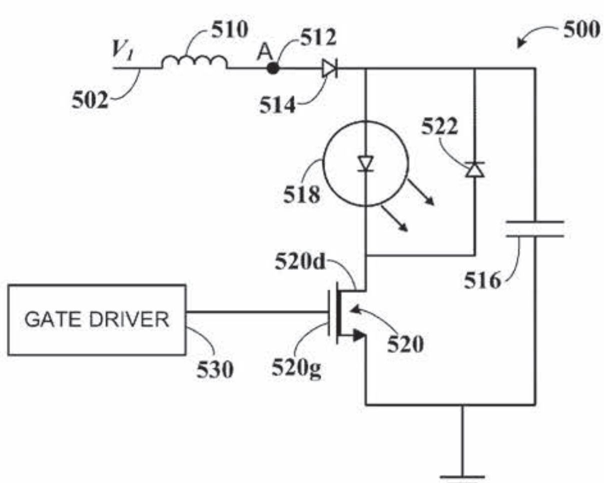
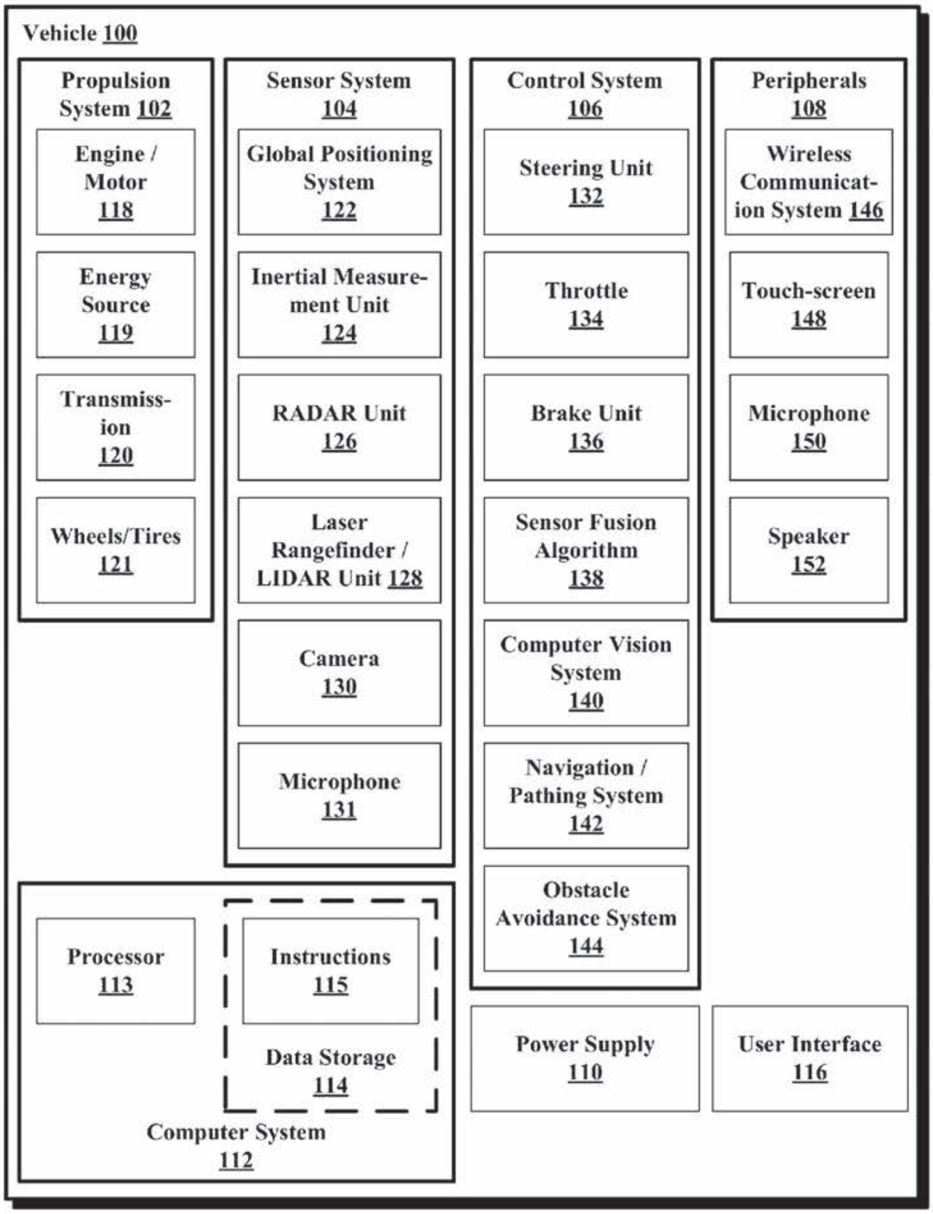
Primary Examiner — Mark Hellner
(74) *Attorney, Agent, or Firm* — McDonnell Boehnen Hulbert & Berghoff LLP

(57) **ABSTRACT**

A laser diode firing circuit for a light detection and ranging device is disclosed. The firing circuit includes a laser diode coupled in series to a transistor, such that current through the laser diode is controlled by the transistor. The laser diode is configured to emit a pulse of light in response to current flowing through the laser diode. The firing circuit includes a capacitor that is configured to charge via a charging path that includes an inductor and to discharge via a discharge path that includes the laser diode. The transistor controlling current through the laser diode can be a Gallium nitride field effect transistor.

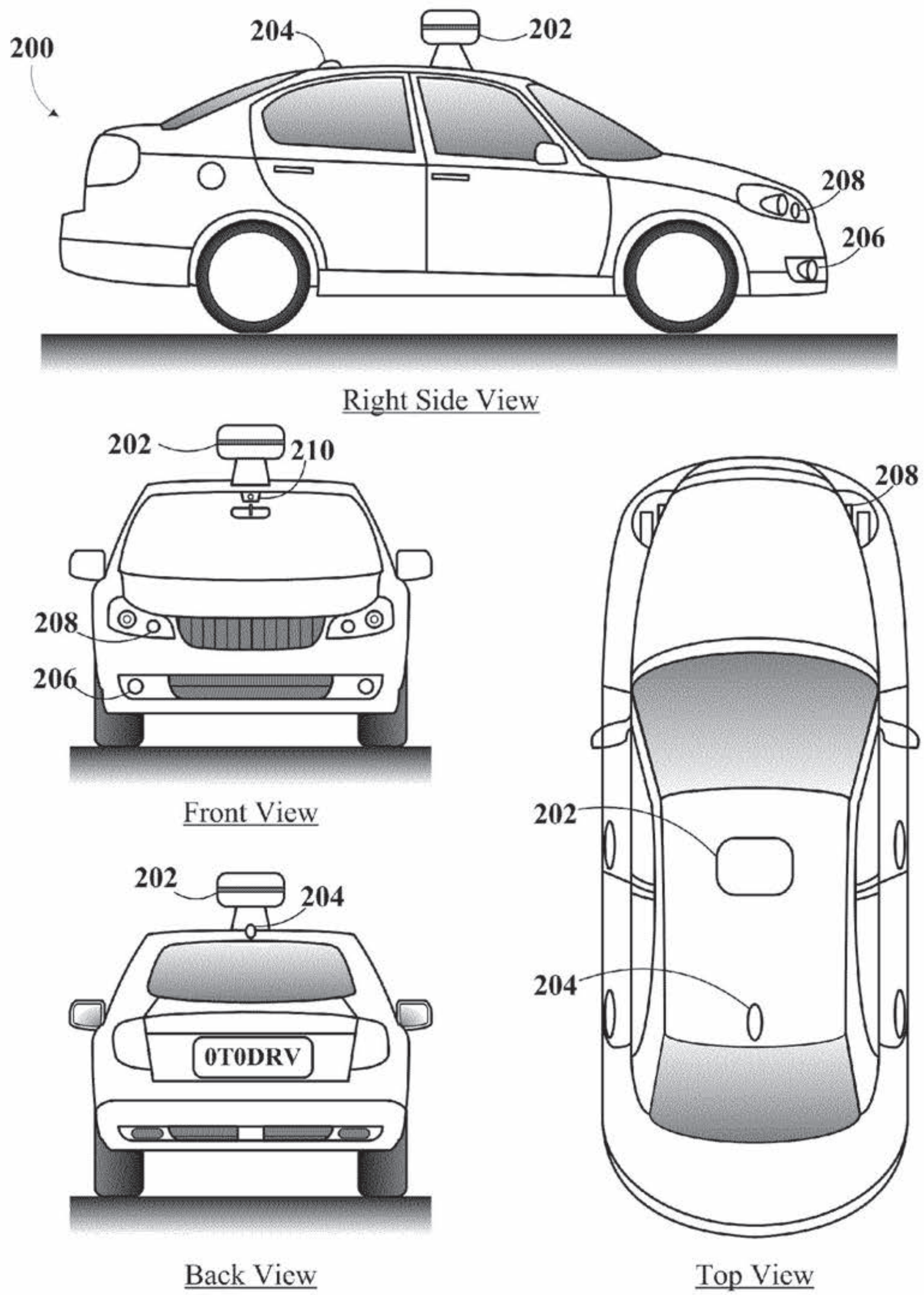
20 Claims, 11 Drawing Sheets





Vehicle 100
Propulsion System 102
Engine / Motor 118
Energy Source 119
Transmission 120
Wheels/Tires 121
Sensor System 104
Global Positioning System 122
Inertial Measurement Unit 124
RADAR Unit 126
Laser Rangefinder / LIDAR Unit 128
Camera 130
Microphone 131
Control System 106
Steering Unit 132
Throttle 134
Brake Unit 136
Sensor Fusion Algorithm 138
Computer Vision System 140
Navigation / Pathing System 142
Obstacle Avoidance System 144
Peripherals 108
Wireless Communication System 146
Touch-screen 148
Microphone 150
Speaker 152
Processor 113
Instructions 115
Data Storage 114
Computer System 112
Power Supply 110
User Interface 116

Figure 1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204
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Right Side View
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Front View
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204
0T0DRV
Back View
Top View

Figure 2

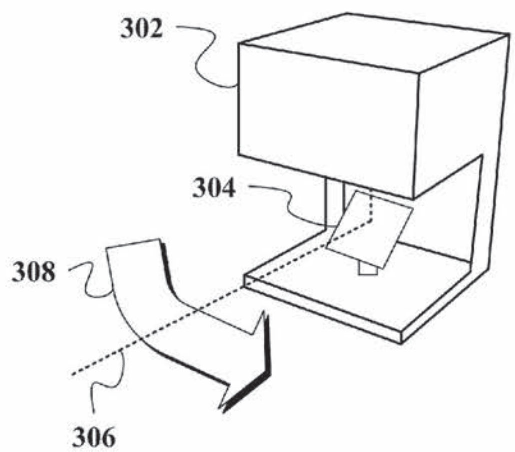


Figure 3A

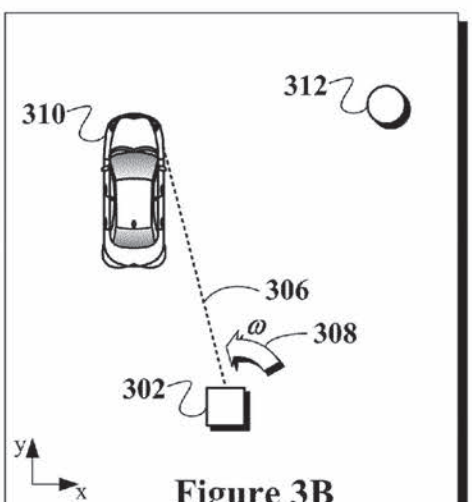


Figure 3B

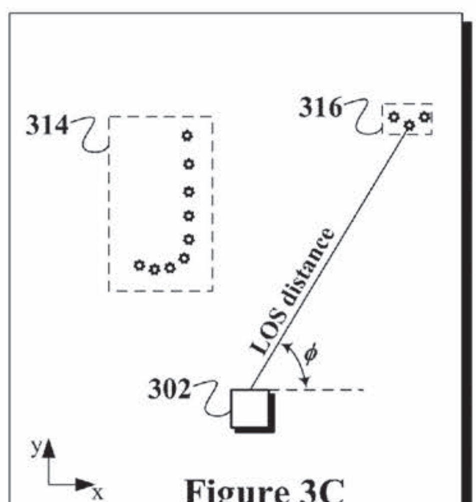


Figure 3C

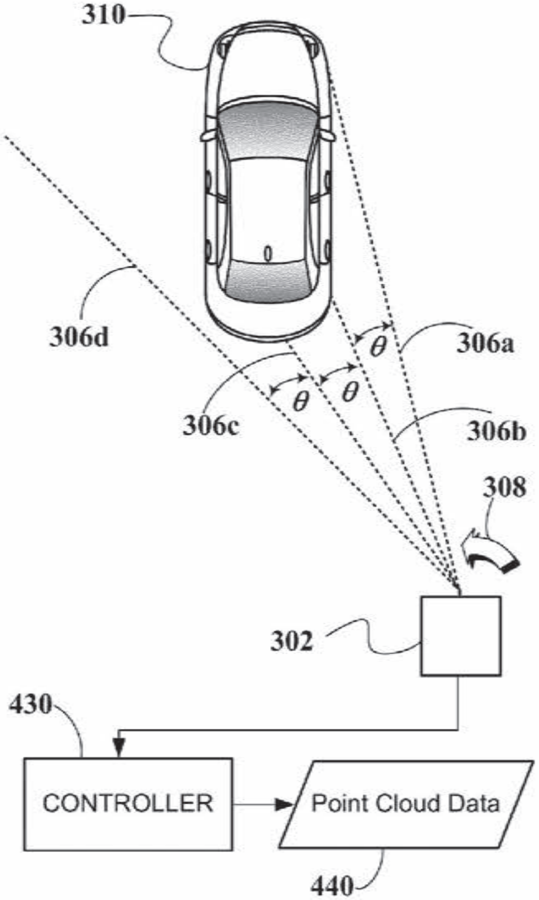


Figure 4A

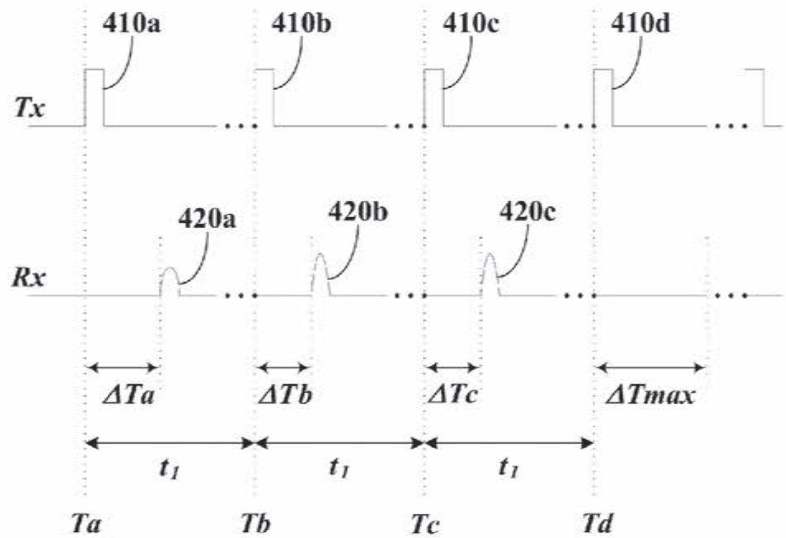


Figure 4B

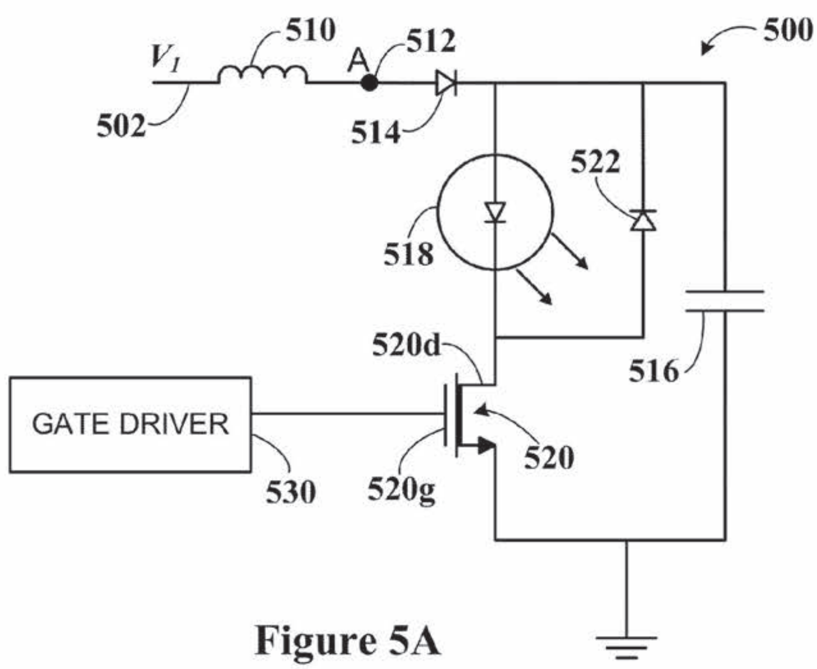


Figure 5A

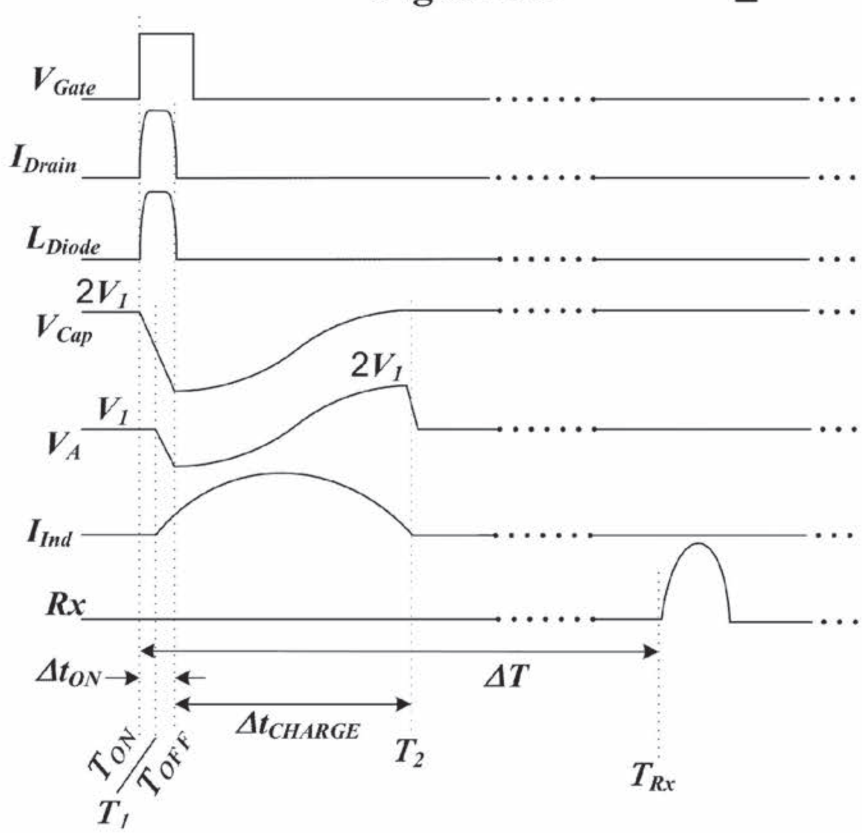


Figure 5B

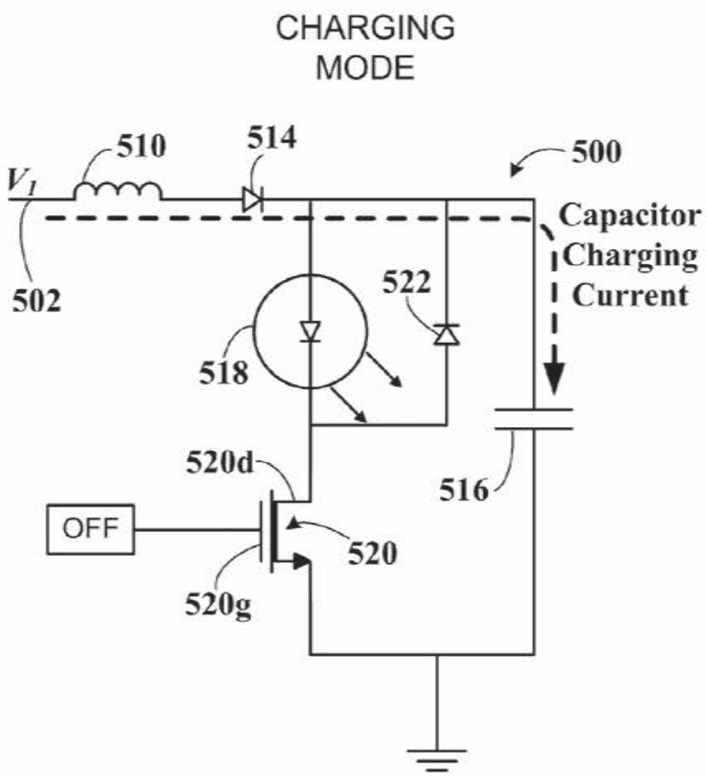


Figure 5C

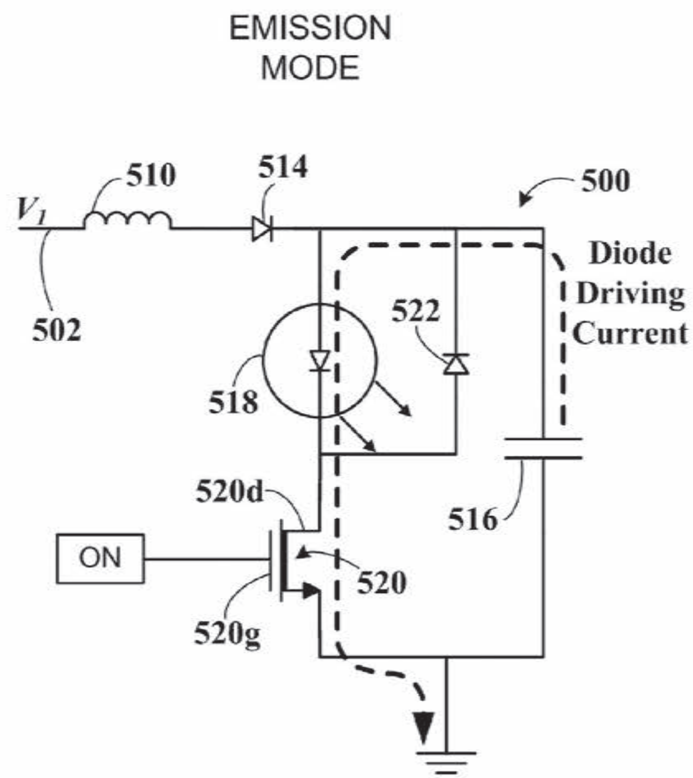
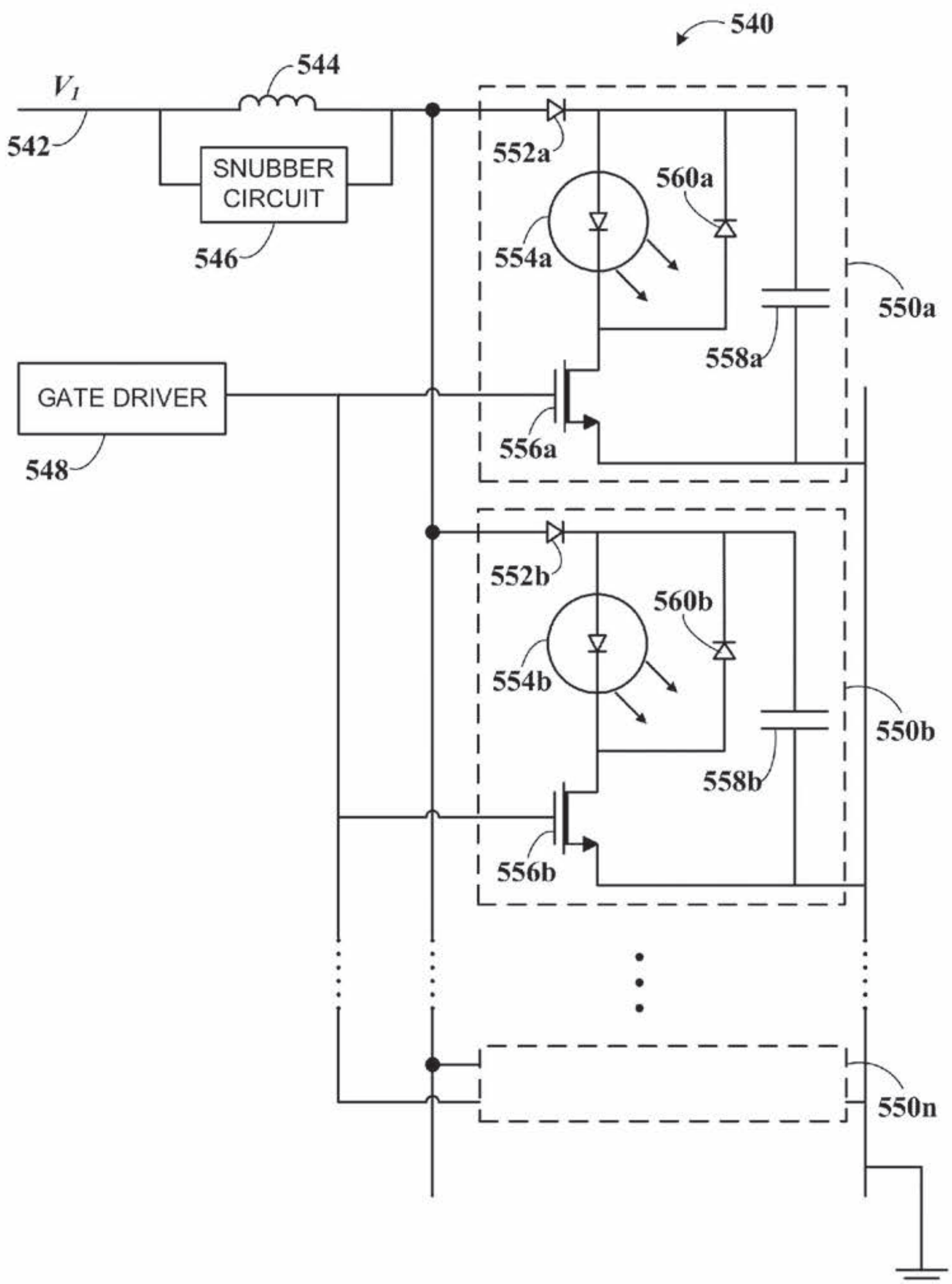


Figure 5D



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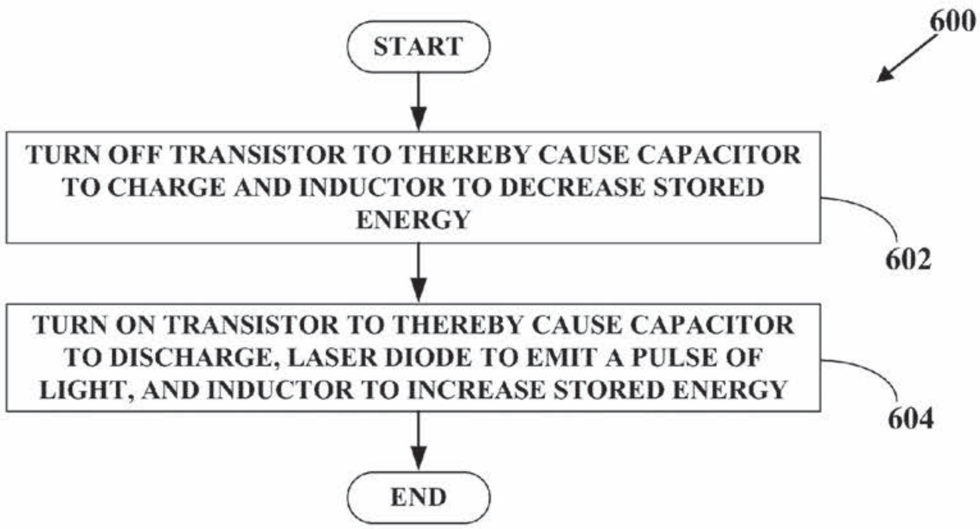
V_1
544
542
SNUBBER CIRCUIT
546
GATE DRIVER
548
552a
560a
554a
550a
558a
556a
552b
560b
554b
550b
558b
556b
550n

Figure 5E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START
TURN OFF TRANSISTOR TO THEREBY CAUSE CAPACITOR TO CHARGE AND INDUCTOR TO DECREASE STORED ENERGY
602
TURN ON TRANSISTOR TO THEREBY CAUSE CAPACITOR TO DISCHARGE, LASER DIODE TO EMIT A PULSE OF LIGHT, AND INDUCTOR TO INCREASE STORED ENERGY
604
END

Figure 6A

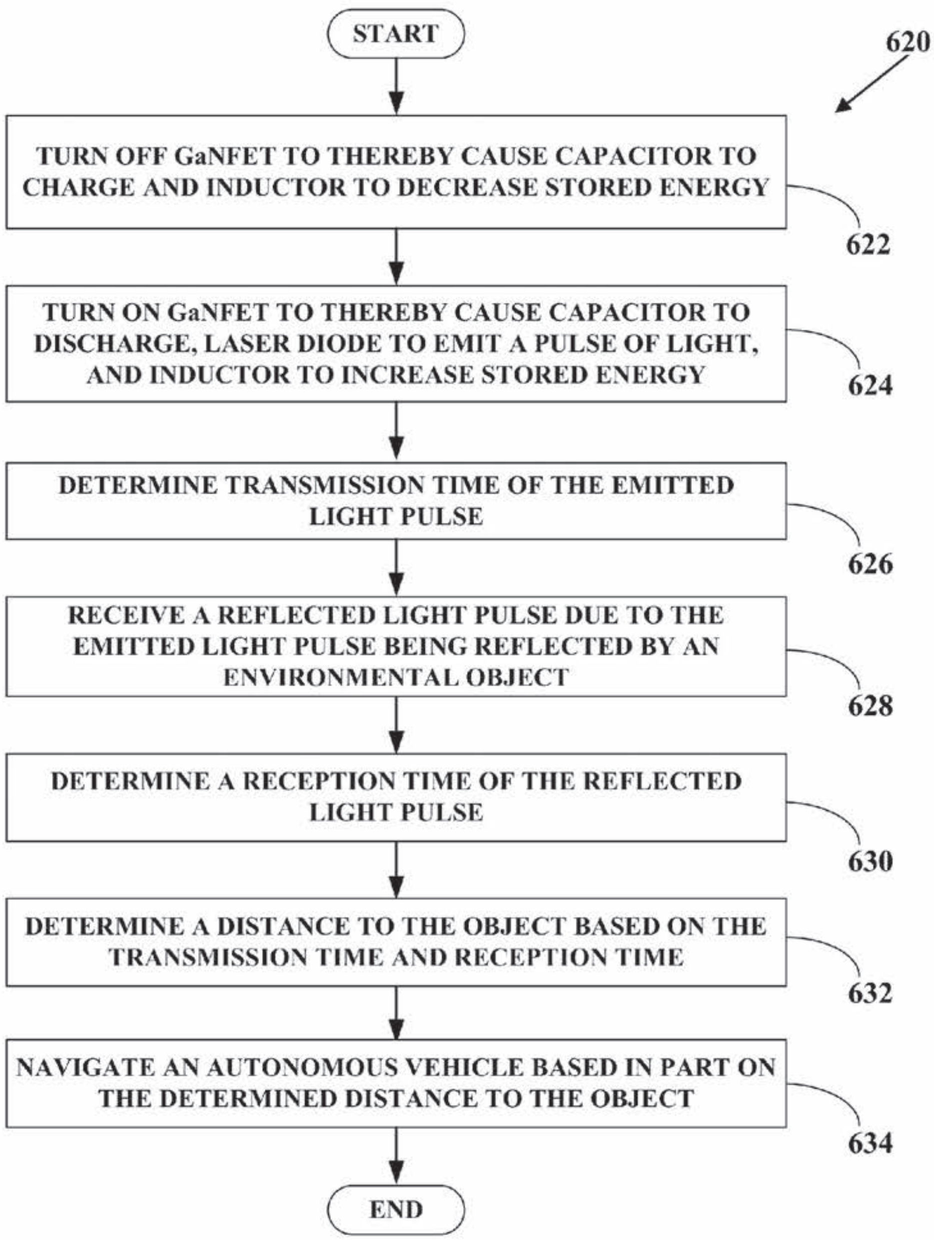
START
620
TURN OFF GaNFET TO THEREBY CAUSE CAPACITOR TO CHARGE AND INDUCTOR TO DECREASE STORED ENERGY
622
TURN ON GaNFET TO THEREBY CAUSE CAPACITOR TO DISCHARGE, LASER DIODE TO EMIT A PULSE OF LIGHT, AND INDUCTOR TO INCREASE STORED ENERGY
624
DETERMINE TRANSMISSION TIME OF THE EMITTED LIGHT PULSE
626
RECEIVE A REFLECTED LIGHT PULSE DUE TO THE EMITTED LIGHT PULSE BEING REFLECTED BY AN ENVIRONMENTAL OBJECT
628
DETERMINE A RECEPTION TIME OF THE REFLECTED LIGHT PULSE
630
DETERMINE A DISTANCE TO THE OBJECT BASED ON THE TRANSMISSION TIME AND RECEPTION TIME
632
NAVIGATE AN AUTONOMOUS VEHICLE BASED IN PART ON THE DETERMINED DISTANCE TO THE OBJECT
634
END

Figure 6B

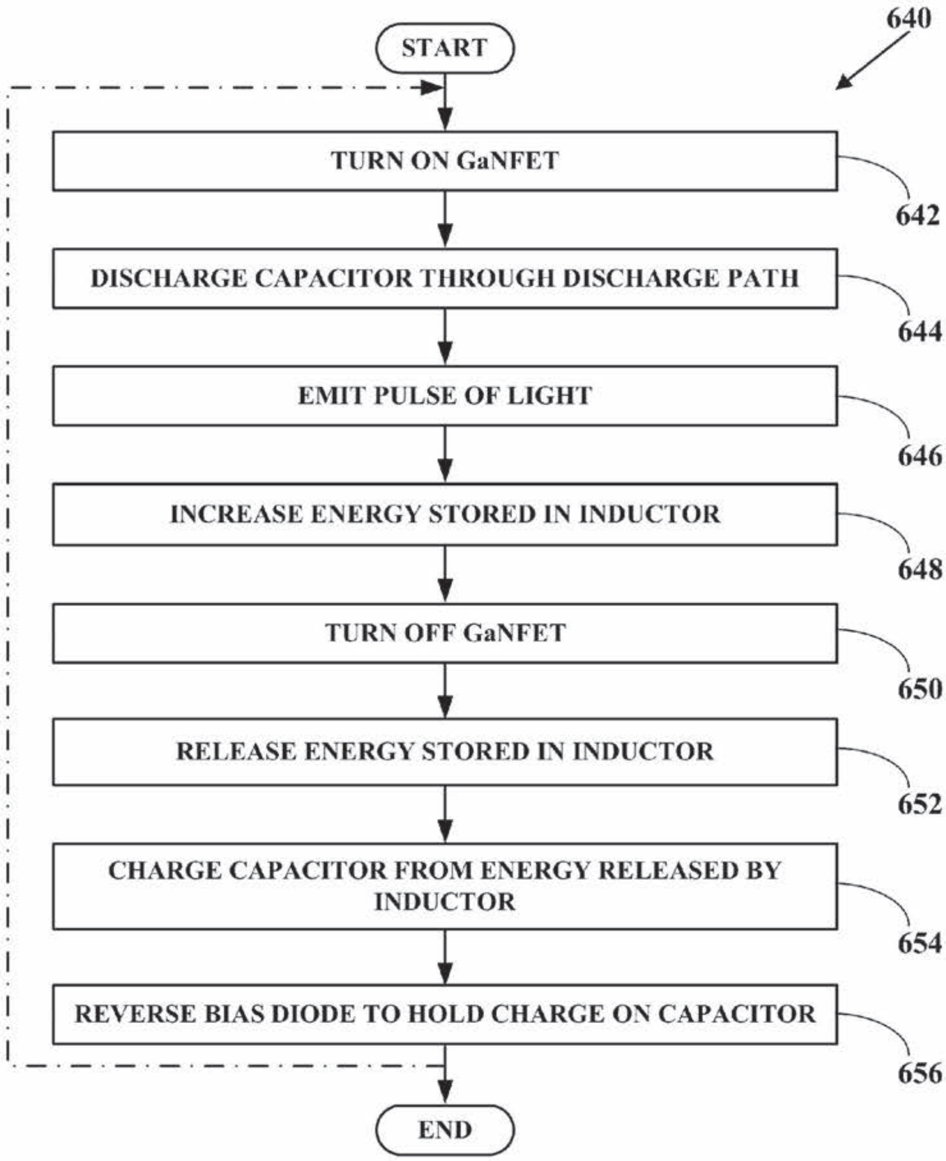
640
START
TURN ON GaNFET
642
DISCHARGE CAPACITOR THROUGH DISCHARGE PATH
644
EMIT PULSE OF LIGHT
646
INCREASE ENERGY STORED IN INDUCTOR
648
TURN OFF GaNFET
650
RELEASE ENERGY STORED IN INDUCTOR
652
CHARGE CAPACITOR FROM ENERGY RELEASED BY INDUCTOR
654
REVERSE BIAS DIODE TO HOLD CHARGE ON CAPACITOR
656
END

Figure 6C

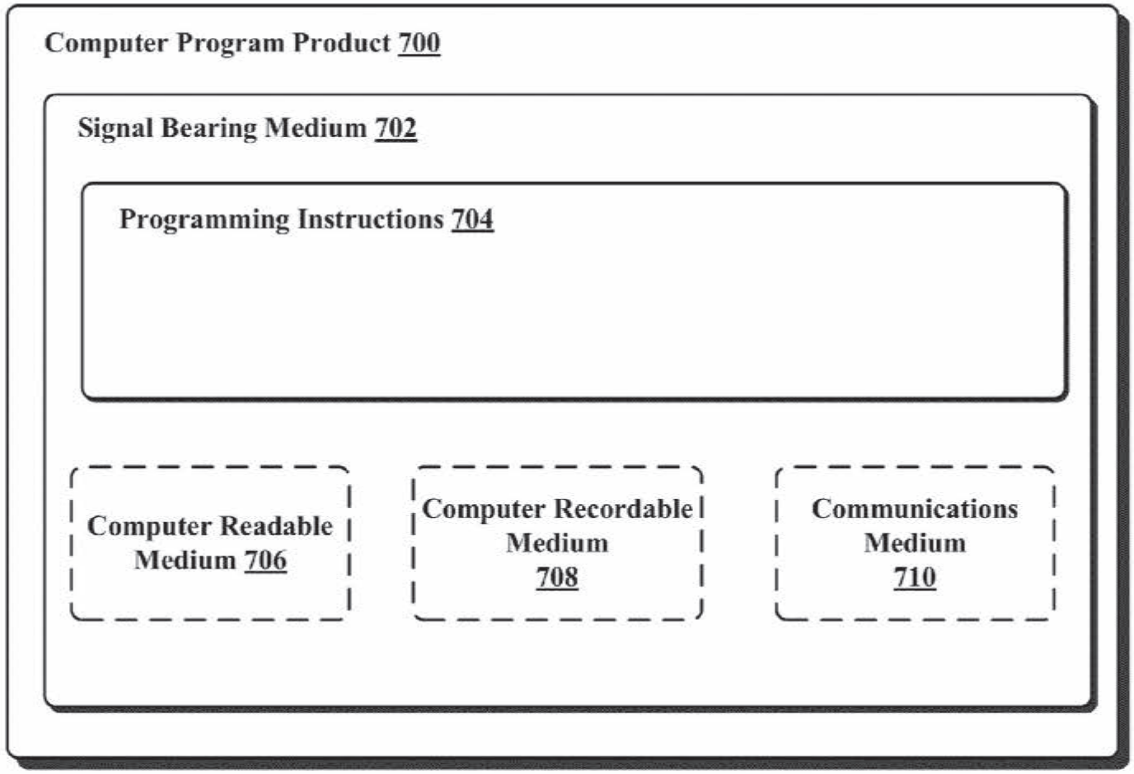
Computer Program Product 700
Signal Bearing Medium 702
Programming Instructions 704
Computer Readable Medium 706
Computer Recordable Medium 708
Communications Medium 710

Figure 7

LASER DIODE FIRING SYSTEM

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority to U.S. Provisional Patent Application No. 61/884,762, filed Sep. 30, 2013, which is incorporated herein by reference in its entirety and for all purposes.

BACKGROUND

Unless otherwise indicated herein, the materials described in this section are not prior art to the claims in this application and are not admitted to be prior art by inclusion in this section.

Vehicles can be configured to operate in an autonomous mode in which the vehicle navigates through an environment with little or no input from a driver. Such autonomous vehicles can include one or more sensors that are configured to detect information about the environment in which the vehicle operates. The vehicle and its associated computer-implemented controller use the detected information to navigate through the environment. For example, if the sensor(s) detect that the vehicle is approaching an obstacle, as determined by the computer-implemented controller, the controller adjusts the vehicle's directional controls to cause the vehicle to navigate around the obstacle.

One such sensor is a light detection and ranging (LIDAR) device. A LIDAR actively estimates distances to environmental features while scanning through a scene to assemble a cloud of point positions indicative of the three-dimensional shape of the environmental scene. Individual points are measured by generating a laser pulse and detecting a returning pulse, if any, reflected from an environmental object, and determining the distance to the reflective object according to the time delay between the emitted pulse and the reception of the reflected pulse. The laser, or set of lasers, can be rapidly and repeatedly scanned across a scene to provide continuous real-time information on distances to reflective objects in the scene. Combining the measured distances and the orientation of the laser(s) while measuring each distance allows for associating a three-dimensional position with each returning pulse. A three-dimensional map of points of reflective features is generated based on the returning pulses for the entire scanning zone. The three-dimensional point map thereby indicates positions of reflective objects in the scanned scene.

SUMMARY

A laser diode firing circuit for a light detection and ranging (LIDAR) device is disclosed. The firing circuit includes a laser diode coupled in series with a transistor, such that current through the laser diode is controlled by the transistor. The laser diode is configured to emit a pulse of light in response to current flowing through the laser diode. A capacitor is connected across the laser diode and the transistor such that the capacitor discharges through the laser diode when the transistor is turned on. The capacitor is charged by a voltage source via a charging path that includes a diode and an inductor. The inductor has one terminal coupled to the voltage source and another terminal coupled to the anode of the diode, and the cathode of the diode is coupled to the capacitor. As a result, the capacitor is only charged while the diode is forward biased. Upon turning on the transistor, the capacitor discharges through the laser diode and a pulse of light is emitted. Once the capacitor discharges to a voltage level sufficient to forward bias the diode, current begins flowing through the inductor. The increase in inductor current causes the inductor to increase energy stored in its magnetic field, and drives the voltage applied to the anode of the diode lower than the voltage source. Once the transistor is turned off, the laser diode ceases emission, and the current through the inductor is directed to recharge the capacitor, which causes the inductor current to begin decreasing. The sudden change in current through the inductor causes an increase in the voltage applied to the anode of the diode. The capacitor is charged until the voltage of the capacitor approximately matches the voltage at the diode anode, at which point the diode becomes reverse biased. Upon reverse biasing the diode, the current through the inductor goes to zero and the charging cycle is complete. Both the emission and charging operations of the firing circuit can thus be controlled by operation of the single transistor.

Some embodiments of the present disclosure provide an apparatus. The apparatus includes a voltage source, an inductor, a diode, a transistor, a light emitting element, and a capacitor. The inductor can be coupled to the voltage source. The inductor can be configured to store energy in a magnetic field. The diode can be coupled to the voltage source via the inductor. The transistor can be configured to be turned on and turned off by a control signal. The light emitting element can be coupled to the transistor. The capacitor can be coupled to a charging path and a discharge path. The charging path can include the inductor and the diode. The discharge path can include the transistor and the light emitting element. The capacitor can be configured to charge via the charging path such that a voltage across the capacitor increases from a lower voltage level to a higher voltage level responsive to the transistor being turned off. The inductor can be configured to release energy stored in the magnetic field such that a current through the inductor decreases from a higher current level to a lower current level responsive to the transistor being turned off. The capacitor can be configured to discharge through the discharge path such that the light emitting element emits a pulse of light and the voltage across the capacitor decreases from the higher voltage level to the lower voltage level responsive to the transistor being turned on. The inductor can be configured to store energy in the magnetic field such that the current through the inductor increases from the lower current level to the higher current level responsive to the transistor being turned on.

Some embodiments of the present disclosure provide a method. The method can include turning off a transistor and turning on a transistor. The transistor can be coupled to a light emitting element. Both the transistor and the light emitting element can be included in a discharge path coupled to a capacitor. The capacitor can also be coupled to a charging path including a diode and an inductor. The inductor can be configured to store energy in a magnetic field. The diode can be coupled to a voltage source via the inductor. The capacitor can be configured to charge via the charging path such that a voltage across the capacitor increases from a lower voltage level to a higher voltage level responsive to the transistor being turned off. The inductor can be configured to release energy stored in the magnetic field such that a current through the inductor decreases from a higher current level to a lower current level responsive to the transistor being turned off. The capacitor can be configured to discharge through the discharge path such that the light emitting element emits a pulse of light and the voltage across the capacitor decreases from the higher voltage level to the lower voltage level responsive to the transistor being turned on. The inductor can be configured to store energy in the magnetic field such that the current

through the inductor increases from the lower current level to the higher current level responsive to the transistor being turned on.

Some embodiments of the present disclosure provide a light detection and ranging (LIDAR) device. The LIDAR device can include a light source, a light sensor, and a controller. The light source can include a voltage source, an inductor, a diode, a transistor, a light emitting element, and a capacitor. The inductor can be coupled to the voltage source. The inductor can be configured to store energy in a magnetic field. The diode can be coupled to the voltage source via the inductor. The transistor can be configured to be turned on and turned off by a control signal. The light emitting element can be coupled to the transistor. The capacitor can be coupled to a charging path and a discharge path. The charging path includes the inductor and the diode. The discharge path includes the transistor and the light emitting element. The capacitor can be configured to charge via the charging path such that a voltage across the capacitor increases from a lower voltage level to a higher voltage level responsive to the transistor being turned off. The inductor can be configured to release energy stored in the magnetic field such that a current through the inductor decreases from a higher current level to a lower current level responsive to the transistor being turned off. The capacitor can be configured to discharge through the discharge path such that the light emitting element emits a pulse of light and the voltage across the capacitor decreases from the higher voltage level to the lower voltage level responsive to the transistor being turned on. The inductor can be configured to store energy in the magnetic field such that the current through the inductor increases from the lower current level to the higher current level responsive to the transistor being turned on. The light sensor can be configured to detect a reflected light signal comprising light from the emitted light pulse reflected by a reflective object. The controller can be configured to determine a distance to the reflective object based on the reflected light signal.

Some embodiments of the present disclosure provide a means for controlling a laser diode firing circuit to operate in an emission mode and a charging mode using a single transistor. Embodiments may include means turning off a transistor and turning on a transistor. The transistor can be coupled to a light emitting element. Both the transistor and the light emitting element can be included in a discharge path coupled to a capacitor. The capacitor can also be coupled to a charging path including a diode and an inductor. The inductor can be configured to store energy in a magnetic field. The diode can be coupled to a voltage source via the inductor. The capacitor can be configured to charge via the charging path such that a voltage across the capacitor increases from a lower voltage level to a higher voltage level responsive to the transistor being turned off. The inductor can be configured to release energy stored in the magnetic field such that a current through the inductor decreases from a higher current level to a lower current level responsive to the transistor being turned off. The capacitor can be configured to discharge through the discharge path such that the light emitting element emits a pulse of light and the voltage across the capacitor decreases from the higher voltage level to the lower voltage level responsive to the transistor being turned on. The inductor can be configured to store energy in the magnetic field such that the current through the inductor increases from the lower current level to the higher current level responsive to the transistor being turned on.

These as well as other aspects, advantages, and alternatives, will become apparent to those of ordinary skill in the art by reading the following detailed description, with reference where appropriate to the accompanying drawings.

BRIEF DESCRIPTION OF THE FIGURES

FIG. **1** is a functional block diagram depicting aspects of an example autonomous vehicle.

FIG. **2** depicts exterior views of an example autonomous vehicle.

FIG. **3**A provides an example depiction of a LIDAR device including beam steering optics.

FIG. **3**B symbolically illustrates an example in which a LIDAR device scans across an obstacle-filled environmental scene.

FIG. **3**C symbolically illustrates an example point cloud corresponding to the obstacle-filled environmental scene of FIG. **3**B.

FIG. **4**A symbolically illustrates a LIDAR device scanning across an example obstacle-filled environmental scene and using reflected signals to generate a point cloud.

FIG. **4**B is an example timing diagram of transmitted and received pulses for the symbolic illustration of FIG. **4**A.

FIG. **5**A is an example laser diode firing circuit.

FIG. **5**B is a timing diagram that shows operation of the example laser diode firing circuit of FIG. **5**A.

FIG. **5**C shows a current path through the example laser diode firing circuit of FIG. **5**A during a charging mode.

FIG. **5**D shows a current path through the example laser diode firing circuit of FIG. **5**A during an emission mode.

FIG. **5**E illustrates an arrangement in which multiple laser diode firing circuit are charged via a single inductor.

FIG. **6**A is a flowchart of an example process for operating a laser diode firing circuit.

FIG. **6**B is a flowchart of an example process for operating a LIDAR device.

FIG. **6**C is a flowchart of another example process for operating a laser diode firing circuit.

FIG. **7** depicts a non-transitory computer-readable medium configured according to an example embodiment.

DETAILED DESCRIPTION

I. Overview

Example embodiments relate to an autonomous vehicle, such as a driverless automobile, that includes a light detection and ranging (LIDAR) sensor for actively detecting reflective features in the environment surrounding the vehicle. A controller analyzes information from the LIDAR sensor to identify the surroundings of the vehicle. The LIDAR sensor includes a light source that may include one or more laser diodes configured to emit pulses of light that are then directed to illuminate the environment surrounding the vehicle. Circuits for firing a laser diode and determining a pulse emission time from the laser diode are disclosed herein.

According to some embodiments, a LIDAR device includes one or more laser diode firing circuits in which a laser diode is connected in series to a transistor such that current through the laser diode is controlled by the transistor. A capacitor is coupled to a charging path and a discharge path. The discharge path includes the laser diode and the transistor such that turning on the transistor causes the capacitor to discharge through the laser diode, which causes the laser diode to emit a pulse of light.

The capacitor's charging path includes an inductor and a diode. The inductor is configured to store energy in a magnetic field, and is connected between a voltage source and the

diode. An increasing inductor current charges the inductor by increasing the energy stored in the magnetic field of the inductor. The increasing current induces a voltage across the inductor, such that a voltage less than the voltage source is applied to the diode. A decreasing inductor current discharges the inductor by decreasing the energy stored in the magnetic field. The decreasing current induces a voltage across the inductor, such that the voltage applied to the diode exceeds the voltage source. The diode is also connected to the capacitor and is configured to be forward biased when the voltage across the capacitor does not exceed the voltage applied to the diode by the inductor (to thereby charge the capacitor). The diode is also configured to be reverse biased when the voltage across the capacitor exceeds the voltage applied to the diode by the inductor (to thereby prevent the capacitor from discharging).

In some embodiments, the firing circuit disclosed herein is configured to switch between a charging mode and an emission mode based on operation of a single transistor. In response to turning the transistor off, current through the laser diode ceases and emission of a pulse terminates. In response to turning off the transistor, if the charging path diode is forward biased, the capacitor begins recharging through the charging path. As charge accumulates on the capacitor the current through the charging path (and the inductor) decreases, and the decrease in inductor current causes the inductor to release energy stored in its magnetic field. The released energy from the inductor causes the voltage applied to the capacitor through the diode to exceed the voltage of the voltage source, at least transiently. The transient voltage is applied to the capacitor through the diode. The capacitor is therefore charged according to the transient voltage and then holds its charge level when the diode becomes reverse biased. Following a charging interval, the voltage charged across the capacitor can be greater than the voltage of the voltage source.

The laser diode can emit light in the visible spectrum, ultraviolet spectrum, infrared spectrum, near infrared spectrum, and/or infrared spectrum. In one example, the laser diode emits pulses of infrared light with a wavelength of about 905 nm. The transistor can be a Gallium nitride field effect transistor (FET), for example.

II. Example Autonomous Vehicle System

Some aspects of the example methods described herein may be carried out in whole or in part by an autonomous vehicle or components thereof. However, some example methods may also be carried out in whole or in part by a system or systems that are remote from an autonomous vehicle. For instance, an example method could be carried out in part or in full by a server system, which receives information from sensors (e.g., raw sensor data and/or information derived therefrom) of an autonomous vehicle. Other examples are also possible.

Example systems within the scope of the present disclosure will now be described in greater detail. An example system may be implemented in, or may take the form of, an automobile. However, an example system may also be implemented in or take the form of other vehicles, such as cars, trucks, motorcycles, buses, boats, airplanes, helicopters, lawn mowers, earth movers, boats, snowmobiles, aircraft, recreational vehicles, amusement park vehicles, farm equipment, construction equipment, trams, golf carts, trains, and trolleys. Other vehicles are possible as well.

FIG. **1** is a functional block diagram illustrating a vehicle **100** according to an example embodiment. The vehicle **100** is configured to operate fully or partially in an autonomous mode, and thus may be referred to as an "autonomous vehicle." For example, a computer system **112** can control the vehicle **100** while in an autonomous mode via control instructions to a control system **106** for the vehicle **100**. The computer system **112** can receive information from one or more sensor systems **104**, and base one or more control processes (such as setting a heading so as to avoid a detected obstacle) upon the received information in an automated fashion.

The autonomous vehicle **100** can be fully autonomous or partially autonomous. In a partially autonomous vehicle some functions can optionally be manually controlled (e.g., by a driver) some or all of the time. Further, a partially autonomous vehicle can be configured to switch between a fully-manual operation mode and a partially-autonomous and/or a fully-autonomous operation mode.

The vehicle **100** includes a propulsion system **102**, a sensor system **104**, a control system **106**, one or more peripherals **108**, a power supply **110**, a computer system **112**, and a user interface **116**. The vehicle **100** may include more or fewer subsystems and each subsystem can optionally include multiple components. Further, each of the subsystems and components of vehicle **100** can be interconnected and/or in communication. Thus, one or more of the functions of the vehicle **100** described herein can optionally be divided between additional functional or physical components, or combined into fewer functional or physical components. In some further examples, additional functional and/or physical components may be added to the examples illustrated by FIG. **1**.

The propulsion system **102** can include components operable to provide powered motion to the vehicle **100**. In some embodiments the propulsion system **102** includes an engine/motor **118**, an energy source **119**, a transmission **120**, and wheels/tires **121**. The engine/motor **118** converts energy source **119** to mechanical energy. In some embodiments, the propulsion system **102** can optionally include one or both of engines and/or motors. For example, a gas-electric hybrid vehicle can include both a gasoline/diesel engine and an electric motor.

The energy source **119** represents a source of energy, such as electrical and/or chemical energy, that may, in full or in part, power the engine/motor **118**. That is, the engine/motor **118** can be configured to convert the energy source **119** to mechanical energy to operate the transmission. In some embodiments, the energy source **119** can include gasoline, diesel, other petroleum-based fuels, propane, other compressed gas-based fuels, ethanol, solar panels, batteries, capacitors, flywheels, regenerative braking systems, and/or other sources of electrical power, etc. The energy source **119** can also provide energy for other systems of the vehicle **100**.

The transmission **120** includes appropriate gears and/or mechanical elements suitable to convey the mechanical power from the engine/motor **118** to the wheels/tires **121**. In some embodiments, the transmission **120** includes a gearbox, a clutch, a differential, a drive shaft, and/or axle(s), etc.

The wheels/tires **121** are arranged to stably support the vehicle **100** while providing frictional traction with a surface, such as a road, upon which the vehicle **100** moves. Accordingly, the wheels/tires **121** are configured and arranged according to the nature of the vehicle **100**. For example, the wheels/tires can be arranged as a unicycle, bicycle, motorcycle, tricycle, or car/truck four-wheel format. Other wheel/tire geometries are possible, such as those including six or more wheels. Any combination of the wheels/tires **121** of vehicle **100** may be operable to rotate differentially with respect to other wheels/tires **121**. The wheels/tires **121** can optionally include at least one wheel that is rigidly attached to the transmission **120** and at least one tire coupled to a rim of

a corresponding wheel that makes contact with a driving surface. The wheels/tires **121** may include any combination of metal and rubber, and/or other materials or combination of materials.

The sensor system **104** generally includes one or more sensors configured to detect information about the environment surrounding the vehicle **100**. For example, the sensor system **104** can include a Global Positioning System (GPS) **122**, an inertial measurement unit (IMU) **124**, a RADAR unit **126**, a laser rangefinder/LIDAR unit **128**, a camera **130**, and/or a microphone **131**. The sensor system **104** could also include sensors configured to monitor internal systems of the vehicle **100** (e.g., O_2 monitor, fuel gauge, engine oil temperature, wheel speed sensors, etc.). One or more of the sensors included in sensor system **104** could be configured to be actuated separately and/or collectively in order to modify a position and/or an orientation of the one or more sensors.

The GPS **122** is a sensor configured to estimate a geographic location of the vehicle **100**. To this end, GPS **122** can include a transceiver operable to provide information regarding the position of the vehicle **100** with respect to the Earth.

The IMU **124** can include any combination of sensors (e.g., accelerometers and gyroscopes) configured to sense position and orientation changes of the vehicle **100** based on inertial acceleration.

The RADAR unit **126** can represent a system that utilizes radio signals to sense objects within the local environment of the vehicle **100**. In some embodiments, in addition to sensing the objects, the RADAR unit **126** and/or the computer system **112** can additionally be configured to sense the speed and/or heading of the objects.

Similarly, the laser rangefinder or LIDAR unit **128** can be any sensor configured to sense objects in the environment in which the vehicle **100** is located using lasers. The laser rangefinder/LIDAR unit **128** can include one or more laser sources, a laser scanner, and one or more detectors, among other system components. The laser rangefinder/LIDAR unit **128** can be configured to operate in a coherent (e.g., using heterodyne detection) or an incoherent detection mode.

The camera **130** can include one or more devices configured to capture a plurality of images of the environment surrounding the vehicle **100**. The camera **130** can be a still camera or a video camera. In some embodiments, the camera **130** can be mechanically movable such as by rotating and/or tilting a platform to which the camera is mounted. As such, a control process of vehicle **100** may be implemented to control the movement of camera **130**.

The sensor system **104** can also include a microphone **131**. The microphone **131** can be configured to capture sound from the environment surrounding vehicle **100**. In some cases, multiple microphones can be arranged as a microphone array, or possibly as multiple microphone arrays.

The control system **106** is configured to control operation(s) regulating acceleration of the vehicle **100** and its components. To effect acceleration, the control system **106** includes a steering unit **132**, throttle **134**, brake unit **136**, a sensor fusion algorithm **138**, a computer vision system **140**, a navigation/pathing system **142**, and/or an obstacle avoidance system **144**, etc.

The steering unit **132** is operable to adjust the heading of vehicle **100**. For example, the steering unit can adjust the axis (or axes) of one or more of the wheels/tires **121** so as to effect turning of the vehicle. The throttle **134** is configured to control, for instance, the operating speed of the engine/motor **118** and, in turn, adjust forward acceleration of the vehicle **100** via the transmission **120** and wheels/tires **121**. The brake unit **136** decelerates the vehicle **100**. The brake unit **136** can use friction to slow the wheels/tires **121**. In some embodiments, the brake unit **136** inductively decelerates the wheels/tires **121** by a regenerative braking process to convert kinetic energy of the wheels/tires **121** to electric current.

The sensor fusion algorithm **138** is an algorithm (or a computer program product storing an algorithm) configured to accept data from the sensor system **104** as an input. The data may include, for example, data representing information sensed at the sensors of the sensor system **104**. The sensor fusion algorithm **138** can include, for example, a Kalman filter, Bayesian network, etc. The sensor fusion algorithm **138** provides assessments regarding the environment surrounding the vehicle based on the data from sensor system **104**. In some embodiments, the assessments can include evaluations of individual objects and/or features in the environment surrounding vehicle **100**, evaluations of particular situations, and/or evaluations of possible interference between the vehicle **100** and features in the environment (e.g., such as predicting collisions and/or impacts) based on the particular situations.

The computer vision system **140** can process and analyze images captured by camera **130** to identify objects and/or features in the environment surrounding vehicle **100**. The detected features/objects can include traffic signals, road way boundaries, other vehicles, pedestrians, and/or obstacles, etc. The computer vision system **140** can optionally employ an object recognition algorithm, a Structure From Motion (SFM) algorithm, video tracking, and/or available computer vision techniques to effect categorization and/or identification of detected features/objects. In some embodiments, the computer vision system **140** can be additionally configured to map the environment, track perceived objects, estimate the speed of objects, etc.

The navigation and pathing system **142** is configured to determine a driving path for the vehicle **100**. For example, the navigation and pathing system **142** can determine a series of speeds and directional headings to effect movement of the vehicle along a path that substantially avoids perceived obstacles while generally advancing the vehicle along a roadway-based path leading to an ultimate destination, which can be set according to user inputs via the user interface **116**, for example. The navigation and pathing system **142** can additionally be configured to update the driving path dynamically while the vehicle **100** is in operation on the basis of perceived obstacles, traffic patterns, weather/road conditions, etc. In some embodiments, the navigation and pathing system **142** can be configured to incorporate data from the sensor fusion algorithm **138**, the GPS **122**, and one or more predetermined maps so as to determine the driving path for vehicle **100**.

The obstacle avoidance system **144** can represent a control system configured to identify, evaluate, and avoid or otherwise negotiate potential obstacles in the environment surrounding the vehicle **100**. For example, the obstacle avoidance system **144** can effect changes in the navigation of the vehicle by operating one or more subsystems in the control system **106** to undertake swerving maneuvers, turning maneuvers, braking maneuvers, etc. In some embodiments, the obstacle avoidance system **144** is configured to automatically determine feasible ("available") obstacle avoidance maneuvers on the basis of surrounding traffic patterns, road conditions, etc. For example, the obstacle avoidance system **144** can be configured such that a swerving maneuver is not undertaken when other sensor systems detect vehicles, construction barriers, other obstacles, etc. in the region adjacent the vehicle that would be swerved into. In some embodiments, the obstacle avoidance system **144** can automatically select the maneuver that is both available and maximizes

safety of occupants of the vehicle. For example, the obstacle avoidance system **144** can select an avoidance maneuver predicted to cause the least amount of acceleration in a passenger cabin of the vehicle **100**.

The vehicle **100** also includes peripherals **108** configured to allow interaction between the vehicle **100** and external sensors, other vehicles, other computer systems, and/or a user, such as an occupant of the vehicle **100**. For example, the peripherals **108** for receiving information from occupants, external systems, etc. can include a wireless communication system **146**, a touchscreen **148**, a microphone **150**, and/or a speaker **152**.

In some embodiments, the peripherals **108** function to receive inputs for a user of the vehicle **100** to interact with the user interface **116**. To this end, the touchscreen **148** can both provide information to a user of vehicle **100**, and convey information from the user indicated via the touchscreen **148** to the user interface **116**. The touchscreen **148** can be configured to sense both touch positions and touch gestures from a user's finger (or stylus, etc.) via capacitive sensing, resistance sensing, optical sensing, a surface acoustic wave process, etc. The touchscreen **148** can be capable of sensing finger movement in a direction parallel or planar to the touchscreen surface, in a direction normal to the touchscreen surface, or both, and may also be capable of sensing a level of pressure applied to the touchscreen surface. An occupant of the vehicle **100** can also utilize a voice command interface. For example, the microphone **150** can be configured to receive audio (e.g., a voice command or other audio input) from a user of the vehicle **100**. Similarly, the speakers **152** can be configured to output audio to the user of the vehicle **100**.

In some embodiments, the peripherals **108** function to allow communication between the vehicle **100** and external systems, such as devices, sensors, other vehicles, etc. within its surrounding environment and/or controllers, servers, etc., physically located far from the vehicle that provide useful information regarding the vehicle's surroundings, such as traffic information, weather information, etc. For example, the wireless communication system **146** can wirelessly communicate with one or more devices directly or via a communication network. The wireless communication system **146** can optionally use 3G cellular communication, such as CDMA, EVDO, GSM/GPRS, and/or 4G cellular communication, such as WiMAX or LTE. Additionally or alternatively, wireless communication system **146** can communicate with a wireless local area network (WLAN), for example, using WiFi. In some embodiments, wireless communication system **146** could communicate directly with a device, for example, using an infrared link, Bluetooth, and/or ZigBee. The wireless communication system **146** can include one or more dedicated short range communication (DSRC) devices that can include public and/or private data communications between vehicles and/or roadside stations. Other wireless protocols for sending and receiving information embedded in signals, such as various vehicular communication systems, can also be employed by the wireless communication system **146** within the context of the present disclosure.

As noted above, the power supply **110** can provide power to components of vehicle **100**, such as electronics in the peripherals **108**, computer system **112**, sensor system **104**, etc. The power supply **110** can include a rechargeable lithium-ion or lead-acid battery for storing and discharging electrical energy to the various powered components, for example. In some embodiments, one or more banks of batteries can be configured to provide electrical power. In some embodiments, the power supply **110** and energy source **119** can be implemented together, as in some all-electric cars.

Many or all of the functions of vehicle **100** can be controlled via computer system **112** that receives inputs from the sensor system **104**, peripherals **108**, etc., and communicates appropriate control signals to the propulsion system **102**, control system **106**, peripherals, etc. to effect automatic operation of the vehicle **100** based on its surroundings. Computer system **112** includes at least one processor **113** (which can include at least one microprocessor) that executes instructions **115** stored in a non-transitory computer readable medium, such as the data storage **114**. The computer system **112** may also represent a plurality of computing devices that serve to control individual components or subsystems of the vehicle **100** in a distributed fashion.

In some embodiments, data storage **114** contains instructions **115** (e.g., program logic) executable by the processor **113** to execute various functions of vehicle **100**, including those described above in connection with FIG. **1**. Data storage **114** may contain additional instructions as well, including instructions to transmit data to, receive data from, interact with, and/or control one or more of the propulsion system **102**, the sensor system **104**, the control system **106**, and the peripherals **108**.

In addition to the instructions **115**, the data storage **114** may store data such as roadway maps, path information, among other information. Such information may be used by vehicle **100** and computer system **112** during operation of the vehicle **100** in the autonomous, semi-autonomous, and/or manual modes to select available roadways to an ultimate destination, interpret information from the sensor system **104**, etc.

The vehicle **100**, and associated computer system **112**, provides information to and/or receives input from, a user of vehicle **100**, such as an occupant in a passenger cabin of the vehicle **100**. The user interface **116** can accordingly include one or more input/output devices within the set of peripherals **108**, such as the wireless communication system **146**, the touchscreen **148**, the microphone **150**, and/or the speaker **152** to allow communication between the computer system **112** and a vehicle occupant.

The computer system **112** controls the operation of the vehicle **100** based on inputs received from various subsystems indicating vehicle and/or environmental conditions (e.g., propulsion system **102**, sensor system **104**, and/or control system **106**), as well as inputs from the user interface **116**, indicating user preferences. For example, the computer system **112** can utilize input from the control system **106** to control the steering unit **132** to avoid an obstacle detected by the sensor system **104** and the obstacle avoidance system **144**. The computer system **112** can be configured to control many aspects of the vehicle **100** and its subsystems. Generally, however, provisions are made for manually overriding automated controller-driven operation, such as in the event of an emergency, or merely in response to a user-activated override, etc.

The components of vehicle **100** described herein can be configured to work in an interconnected fashion with other components within or outside their respective systems. For example, the camera **130** can capture a plurality of images that represent information about an environment of the vehicle **100** while operating in an autonomous mode. The environment may include other vehicles, traffic lights, traffic signs, road markers, pedestrians, etc. The computer vision system **140** can categorize and/or recognize various aspects in the environment in concert with the sensor fusion algorithm **138**, the computer system **112**, etc. based on object recognition models pre-stored in data storage **114**, and/or by other techniques.

Although the vehicle **100** is described and shown in FIG. **1** as having various components of vehicle **100**, e.g., wireless communication system **146**, computer system **112**, data storage **114**, and user interface **116**, integrated into the vehicle **100**, one or more of these components can optionally be mounted or associated separately from the vehicle **100**. For example, data storage **114** can exist, in part or in full, separate from the vehicle **100**, such as in a cloud-based server, for example. Thus, one or more of the functional elements of the vehicle **100** can be implemented in the form of device elements located separately or together. The functional device elements that make up vehicle **100** can generally be communicatively coupled together in a wired and/or wireless fashion.

FIG. **2** shows an example vehicle **200** that can include some or all of the functions described in connection with vehicle **100** in reference to FIG. **1**. Although vehicle **200** is illustrated in FIG. **2** as a four-wheel sedan-type car for illustrative purposes, the present disclosure is not so limited. For instance, the vehicle **200** can represent a truck, a van, a semi-trailer truck, a motorcycle, a golf cart, an off-road vehicle, or a farm vehicle, etc.

The example vehicle **200** includes a sensor unit **202**, a wireless communication system **204**, a RADAR unit **206**, a laser rangefinder unit **208**, and a camera **210**. Furthermore, the example vehicle **200** can include any of the components described in connection with vehicle **100** of FIG. **1**. The RADAR unit **206** and/or laser rangefinder unit **208** can actively scan the surrounding environment for the presence of potential obstacles and can be similar to the RADAR unit **126** and/or laser rangefinder/LIDAR unit **128** in the vehicle **100**.

The sensor unit **202** is mounted atop the vehicle **200** and includes one or more sensors configured to detect information about an environment surrounding the vehicle **200**, and output indications of the information. For example, sensor unit **202** can include any combination of cameras, RADARs, LIDARs, range finders, and acoustic sensors. The sensor unit **202** can include one or more movable mounts that could be operable to adjust the orientation of one or more sensors in the sensor unit **202**. In one embodiment, the movable mount could include a rotating platform that could scan sensors so as to obtain information from each direction around the vehicle **200**. In another embodiment, the movable mount of the sensor unit **202** could be moveable in a scanning fashion within a particular range of angles and/or azimuths. The sensor unit **202** could be mounted atop the roof of a car, for instance, however other mounting locations are possible. Additionally, the sensors of sensor unit **202** could be distributed in different locations and need not be collocated in a single location. Some possible sensor types and mounting locations include RADAR unit **206** and laser rangefinder unit **208**. Furthermore, each sensor of sensor unit **202** can be configured to be moved or scanned independently of other sensors of sensor unit **202**.

In an example configuration, one or more RADAR scanners (e.g., the RADAR unit **206**) can be located near the front of the vehicle **200**, to actively scan the region in front of the car **200** for the presence of radio-reflective objects. A RADAR scanner can be situated, for example, in a location suitable to illuminate a region including a forward-moving path of the vehicle **200** without occlusion by other features of the vehicle **200**. For example, a RADAR scanner can be situated to be embedded and/or mounted in or near the front bumper, front headlights, cowl, and/or hood, etc. Furthermore, one or more additional RADAR scanning devices can be located to actively scan the side and/or rear of the vehicle **200** for the presence of radio-reflective objects, such as by including such devices in or near the rear bumper, side panels, rocker panels, and/or undercarriage, etc.

The wireless communication system **204** could be located on a roof of the vehicle **200** as depicted in FIG. **2**. Alternatively, the wireless communication system **204** could be located, fully or in part, elsewhere. The wireless communication system **204** may include wireless transmitters and receivers that could be configured to communicate with devices external or internal to the vehicle **200**. Specifically, the wireless communication system **204** could include transceivers configured to communicate with other vehicles and/or computing devices, for instance, in a vehicular communication system or a roadway station. Examples of such vehicular communication systems include dedicated short range communications (DSRC), radio frequency identification (RFID), and other proposed communication standards directed towards intelligent transport systems.

The camera **210** can be a photo-sensitive instrument, such as a still camera, a video camera, etc., that is configured to capture a plurality of images of the environment of the vehicle **200**. To this end, the camera **210** can be configured to detect visible light, and can additionally or alternatively be configured to detect light from other portions of the spectrum, such as infrared or ultraviolet light. The camera **210** can be a two-dimensional detector, and can optionally have a three-dimensional spatial range of sensitivity. In some embodiments, the camera **210** can include, for example, a range detector configured to generate a two-dimensional image indicating distance from the camera **210** to a number of points in the environment. To this end, the camera **210** may use one or more range detecting techniques.

For example, the camera **210** can provide range information by using a structured light technique in which the vehicle **200** illuminates an object in the environment with a predetermined light pattern, such as a grid or checkerboard pattern and uses the camera **210** to detect a reflection of the predetermined light pattern from environmental surroundings. Based on distortions in the reflected light pattern, the vehicle **200** can determine the distance to the points on the object. The predetermined light pattern may comprise infrared light, or radiation at other suitable wavelengths for such measurements.

The camera **210** can be mounted inside a front windshield of the vehicle **200**. Specifically, the camera **210** can be situated to capture images from a forward-looking view with respect to the orientation of the vehicle **200**. Other mounting locations and viewing angles of camera **210** can also be used, either inside or outside the vehicle **200**.

The camera **210** can have associated optics operable to provide an adjustable field of view. Further, the camera **210** can be mounted to vehicle **200** with a movable mount to vary a pointing angle of the camera **210**, such as via a pan/tilt mechanism.

III. Example LIDAR Device

An example light detection and ranging (LIDAR) device operates to estimate positions of reflective objects surrounding the device by illuminating its surrounding environment with pulses of light and measuring the reflected signals. An example LIDAR device may include a light source, beam-steering optics, a light sensor, and a controller. The light source may emit pulses of light toward the beam-steering optics, which directs the pulses of light across a scanning zone. Reflective features in the scanning zone reflect the emitted pulses of light and the reflected light signals can be detected by the light sensor. The controller can regulate the

operation of the light source and beam-steering optics to scan pulses of light across the scanning zone. The controller can also be configured to estimate positions of reflective features in the scanning zone based on the reflected signals detected by the light sensor. For example, the controller can measure the time delay between emission of a pulse of light and reception of a reflected light signal and determine the distance to the reflective feature based on the time of flight of a round trip to the reflective feature. In addition, the controller may use the orientation of the beam-steering optics at the time the pulse of light is emitted to estimate a direction toward the reflective feature. The estimated direction and estimated distance can then be combined to estimate a three-dimensional position of the reflective object relative to the LIDAR device.

FIG. **3**A provides an example depiction of a LIDAR device **302** including beam steering optics **304**. A laser beam **306** is directed to the beam steering optics **304**. In the example illustrated in FIG. **3**A, the beam steering optics **304** is a rotating angled mirror that directs the laser beam **306** to sweep across a scanning zone. The beam steering optics **304** may include a combination of lenses, mirrors, and/or apertures configured to direct the laser beam to sweep across a scanning zone, and are interchangeably described as the rotating angled mirror **304**. The rotating angled mirror **304** rotates about an axis substantially parallel, and roughly in line with, the initial downward path of the laser beam **306**. The rotating angled mirror **304** rotates in the direction indicated by the reference arrow **308** in FIG. **3**A.

Although rangefinder **302** is depicted as having an approximately 180 degree range of rotation for the scanning zone of the laser beam **306** via the rotating angled mirror **304**, this is for purposes of example and explanation only. LIDAR **302** can be configured to have viewing angles (e.g., angular range of available orientations during each sweep), including viewing angles up to and including 360 degrees. Further, although LIDAR **302** is depicted with the single laser beam **306** and a single mirror **304**, this is for purposes of example and explanation only, LIDAR **302** can include multiple laser beams operating simultaneously or sequentially to provide greater sampling coverage of the surrounding environment. The LIDAR **302** also includes, or works in concert with, additional optical sensors (e.g., a photo-detector, not shown) configured to detect the reflection of laser beam **306** from features/objects in the surrounding environment with sufficient temporal sensitivity to determine distances to the reflective features. For example, with reference to the vehicle **200** in FIG. **2**, such optical sensors can optionally be co-located with the top-mounted sensors **204** on the autonomous vehicle **200**.

FIG. **3**B symbolically illustrates the LIDAR device **302** scanning across an obstacle-filled environmental scene. The example vehicular environment depicted in FIG. **3**B includes a car **310** and a tree **312**. In operation, LIDAR **302** rotates according to motion reference arrow **308**. While rotating, the LIDAR **302** regularly (e.g., periodically) emits laser pulses, such as the laser pulse **306**. Objects in the surrounding environment, such as vehicle **310** and tree **312**, reflect the emitted pulses and the resulting reflected signals are then received by suitable sensors. Precisely time-stamping the receipt of the reflected signals allows for associating each reflected signal (if any is received at all) with the most recently emitted laser pulse, and measuring the time delay between emission of the laser pulse and reception of the reflected light. The time delay provides an estimate of the distance to the reflective feature by scaling according to the speed of light in the intervening atmosphere. Combining the distance information for each reflected signal with the orientation of the LIDAR device **302** for the respective pulse emission allows for determining a position of the reflective feature in three-dimensions. For illustrative purposes, the environmental scene in FIG. **3**B is described in the two-dimensional x-y plane in connection with a single sweep of the LIDAR device **302** that estimates positions to a series of points located in the x-y plane. However, it is noted that a more complete three-dimensional sampling is provided by either adjusting the beam steering optics **304** to direct the laser beam **306** up or down from the x-y plane on its next sweep of the scene or by providing additional lasers and associated beam steering optics dedicated to sampling point locations in planes above and below the x-y plane shown in FIG. **3**B, or combinations of these techniques.

FIG. **3**C symbolically illustrates a point cloud corresponding to the obstacle-filled environmental scene of FIG. **3**B. Spatial-point data (represented by stars) are shown from a ground-plane (or aerial) perspective. Even though the individual points are not equally spatially distributed throughout the sampled environment, adjacent sampled points are roughly equally angularly spaced with respect to the LIDAR device **302**. A cluster of points referred to herein as car spatial data **314** corresponds to measured points on the surface of the car **310** with a line of sight to the LIDAR device **302**. Similarly, a cluster of points referred to herein as tree spatial data **316** corresponds to measured points on the surface of the tree **312** visible from the LIDAR device **302**. The absence of points between the car spatial data **314** and the tree spatial data **316** indicates an absence of reflective features along the sampled line of sight paths in the plane illustrated.

Each point in the example point cloud illustrated symbolically in FIG. **3**C can be referenced by an azimuth angle ϕ (e.g. orientation of the LIDAR device **302** while emitting the pulse corresponding to the point, which is determined by the orientation of the rotating angled mirror **304**) and a line-of-sight (LOS) distance (e.g., the distance indicated by the time delay between pulse emission and reflected light reception). For emitted pulses that do not receive a reflected signal, the LOS distance can optionally be set to the maximum distance sensitivity of the LIDAR device **302**. The maximum distance sensitivity can be determined according to the maximum time delay the associated optical sensors wait for a return reflected signal following each pulse emission, which can itself be set according to the anticipated signal strength of a reflected signal at a particular distance given ambient lighting conditions, intensity of the emitted pulse, predicted reflectivity of environmental features, etc. In some examples, the maximum distance can be approximately 60 meters, 80 meters, 100 meters, or 150 meters, but other examples are possible for particular configurations of the LIDAR device **302** and associated optical sensors.

In some embodiments, the sensor fusion algorithm **138**, computer vision system **140**, and/or computer system **112**, can interpret the car spatial data **314** alone and/or in combination with additional sensor-indicated information and/or memory-based pattern-matching point clouds and/or baseline maps of the environment to categorize or identify the group of points **314** as corresponding to the car **310**. Similarly, the tree spatial data **316** can identified as corresponding to the tree **310** in accordance with a suitable object-detection technique. As described further herein, some embodiments of the present disclosure provide for identifying a region of the point cloud for study with enhanced resolution scanning technique on the basis of the already-sampled spatial-points.

FIG. **4**A symbolically illustrates a LIDAR device **302** scanning across an example obstacle-filled environmental scene. The LIDAR device **302** scans the laser beam **306** across the environmental scene via its beam steering optics **304** while its laser light source pulses, such that successive pulses are emit-

ted with an angular separation θ_1. Successive pulses are emitted periodically with a temporal separation t_1. For illustrative purposes, the angular separation θ_1 between adjacent, successively emitted pulses is exaggerated in FIG. **4**A to allow individual pulses to be represented in the drawing. As a result of the rotation of the beam steering optics in the LIDAR device **302**, temporally separated pulses (e.g., pulses emitted at times separated by the time t_1) are directed in respective angular orientations separated by the amount of rotation of the beam steering optics during the interval t_1, (e.g., the angle θ_1). A controller **430** is arranged to receive signals from the LIDAR device **302** and/or associated optical sensors to generate point cloud data **440** indicative of the 3-D positions of reflective features in the environmental scene surrounding the LIDAR device **302**.

FIG. **4**B is a timing diagram of the transmitted and received pulses for the exaggerated symbolic illustration of FIG. **4**A. The timing diagram symbolically illustrates the transmitted pulses (labeled on FIG. **4**B as "Tx") and the corresponding received pulses (labeled on FIG. **4**B as "Rx").

An example operation of the LIDAR device **302** is described in connection with FIGS. **4**A and **4**B. At time Ta, a first pulse **410***a* is emitted from the LIDAR device **302** and directed along laser beam path **306***a* via the beam steering optics. As shown in FIG. **4**A, the beam path **306***a* is reflected from near the front passenger-side region of the car **310**, and a first reflected signal **420***a* is detected at optical signals associated with the LIDAR device **302** (e.g., via optical sensors included in the sensor system **202** mounted on the vehicle **200** in FIG. **2**). The time delay between the emission of pulse **410***a* and reception of the reflected signal **420***a* is indicated by time delay ΔTa. The time delay ΔTa and the orientation of the LIDAR device **302** at time Ta, i.e., the direction of laser beam **306***a*, are combined in the controller **430** to map the 3-D position of the reflective point on the front passenger-side region of the car **310**.

Next, at time Tb, a second pulse **410***b* is emitted from the LIDAR device **302** and directed along laser beam path **306***b*. Time Tb is temporally separated from time Ta by the interval time t**1**, and the direction of the laser beam path **306***b* is angularly separated from the direction of laser beam path **306***a* by angular separation θ_1, due to the change in orientation of the beam steering optics in the LIDAR device during the interval t_1. The laser pulse **310***b* is reflected from near the rear passenger-side region of the car **310**, and a second reflected signal **420***b* is detected with a relative time delay ΔTb from the emission of the second pulse **410***b*. As illustrated in FIG. **4**B, the LIDAR device **302** is generally situated behind the car **310**, and so the reflective point near the rear passenger-side region of the car **310** (responsible for the reflected signal **420***b*) is closer to the LIDAR device **302** than the reflective point near the front passenger-side region of the car **310** (responsible for the reflected signal **420***a*). As a result, the relative time delay ΔTb is shorter than the relative time delay ΔTa, corresponding to the difference in roundtrip travel time at the speed of light between the LIDAR device **302**, and the respective reflective points at the front and rear of the car.

Further, the sensors detecting the reflected signals can optionally be sensitive to the intensity of the reflected signals. For example, the intensity of the reflected signal **420***b* can be perceptibly greater than the intensity of the reflected signal **420***a*, as shown symbolically in FIG. **4**B. The controller **430** maps the 3-D position of the reflective point near the rear passenger-side of the car **310** according to the time delay value ΔTb and the orientation of the LIDAR device **310** at time Tb, i.e., the direction of laser beam **306***b*. The intensity of the reflected signal can also indicate the reflectance of the reflective point, in combination with the distance to the point as indicated by the measured time delay. The reflectance of the reflective point can be employed by software and/or hardware implemented modules in the controller **430** to characterize the reflective features in the environment. For example, traffic indicators such as lane markers, traffic signs, traffic signals, navigational signage, etc., can be indicated in part based on having a relatively high reflectance value, such as associated with a reflective coating applied to traffic and/or navigational signage. In some embodiments, identifying a relatively high reflectance feature can provide a prompt to undertake a further scan of the high reflectance feature with one or more sensors, such as those in the sensing system **104**. Thus, in one example, a reflected signal indicating a high reflectance feature can provide a prompt to image the high reflectance feature with a camera to allow for identifying the high reflectance feature. In some embodiments where the high reflectance feature is a traffic sign, the camera image can allow for reading the sign via character recognition and/or pattern matching, etc. and then optionally adjusting navigational instructions based on the sign (e.g., a sign indicating a construction zone, pedestrian crosswalk, school zone, etc. can prompt the autonomous vehicle to reduce speed).

At time Tc, following the time Tb by the interval t**1**, a third pulse **410***c* is emitted from the LIDAR device **302**. The third pulse **410***c* is directed along a laser beam path **306***c*, which is approximately angularly separated from the beam path **306***b* by the angle θ_1. The pulse **410***c* is reflected from a point near the middle of the rear bumper region of the car **310**, and a resulting reflected signal **420***c* is detected at the LIDAR device **302** (or its associated optical sensors). The controller **430** combines the relative time delay ΔTc between the emission of pulse **410***c* and reception of reflected signal **420***c* and the orientation of the LIDAR device **302** at time Tc, i.e., the direction of beam path **306***c*, to map the 3-D position of the reflective point.

At time Td, following time Tc by the interval t_1, a fourth pulse **410***d* is emitted from the LIDAR device **302**. The fourth pulse **410***d* is directed along a laser beam path **306***d*, which is approximately angularly separated from the beam path **306***c* by the angle θ_1. The beam path **306***d* entirely avoids the car **310**, and all other reflective environmental features within a maximum distance sensitivity of the LIDAR device **302**. As discussed above, the maximum distance sensitivity of the LIDAR device **302** is determined by the sensitivity of the associated optical sensors for detecting reflected signals. The maximum relative time delay ΔTmax corresponds to the maximum distance sensitivity of the LIDAR device (i.e., the time for light signals to make a round trip of the maximum distance). Thus, when the optical sensor associated with the LIDAR device **302** does not receive a reflected signal in the period ΔTmax following time Td, the controller **430** determines that no reflective features are present in the surrounding environment along the laser beam path **306***d*.

The reflective points on the car **310** corresponding to the reflected signals **420***a-c* form a subset of points included in a 3-D point cloud map **440** of the environment surrounding the LIDAR device **302**. In addition, the direction of the laser beam **310***d* is noted in the 3-D point cloud map **440** as being absent of reflective features along the line of sight within the maximum distance sensitivity of the LIDAR device **302**, because no reflected signal was received after the duration ΔTmax following the emission of pulse **410***d* at time Td. The points corresponding to laser beam directions **306***a-d* are combined with points spaced throughout the scanning zone (e.g., the region scanned by the LIDAR device **302**), to create a complete 3-D point cloud map, and the results are output as

fixed resolution point cloud data **440** for further analysis by object detection systems, pattern recognition systems, computer vision systems, etc.

IV. Example Laser Diode Firing Circuit

In order to illuminate a scanning zone with pulses of light, a LIDAR device includes one or more light sources that are triggered to emit pulses of light. The light sources may include light emitting elements such as a laser diode or another emissive light source. A laser diode is a semiconductor device including a p-n junction with an active region in which oppositely polarized, energized charge carriers (e.g., free electrons and/or holes) recombine while current flows through the device across the p-n junction. The recombination results in emission of light due to a change in energy state of the charge carriers. When the active region is heavily populated by such energized pairs (e.g., the active region may have a population inversion of energized states), stimulated emission across the active region may produce a substantially coherent wave front of light that is then emitted from the laser diode. Recombination events, and the resulting light emission, occur in response to current flowing through the device, and so applying a pulse of current to the laser diode results in emission of a pulse of light from the laser diode.

A light pulse with the desired temporal profile can be generated by applying a rapidly switched current to a laser diode (e.g., a current source that rapidly transitions from near zero current to a current sufficient to cause the laser diode to emit light). Circuits configured to convey such currents to laser diodes to cause the laser diodes to fire (e.g., emit a pulse of light) are referred to herein as laser diode firing circuits. One example laser diode firing circuit includes a laser diode connected in series with a transistor capable of switching large currents over brief transition times. Current through the laser diode, and thus emission from the laser diode, can then be controlled by operating the transistor. An example circuit may switch from near zero current through the laser diode, to about 30 amperes, and back to near zero all in a span of about 1-2 nanoseconds.

The firing circuits disclosed herein may include a laser diode configured to emit a pulse of light with a wavelength in the visible spectrum, ultraviolet spectrum, near infrared spectrum, and/or infrared spectrum. In one example, the laser diode is configured to emit a pulse of light in the infrared spectrum with a wavelength of about 905 nanometers.

FIG. **5**A is an example laser diode firing circuit **500**. The firing circuit **500** includes a capacitor **516** connected to a laser diode **518** and a transistor **520**. In some examples, the capacitor **516**, laser diode **518**, and transistor **520** can be connected in series. The capacitor **516** is connected to both a charging path (e.g., FIG. **5**C) and a discharge path (e.g., FIG. **5**D). The capacitor **516** has one terminal coupled to a voltage source **502** (e.g., through inductor **510** and diode **514**) and an anode of the laser diode **518**. The other terminal of the capacitor **516** can be connected to ground, or to another reference voltage sufficient to allow the capacitor **516** to be charged by the voltage source **502**, through the charging path. The cathode of the laser diode **518** is connected to one terminal of the transistor **520**, which has another terminal connected to ground (which may also connect to the capacitor **516**). The transistor **520** acts as a switch to selectively allow current to flow through the laser diode **518** according to a control signal from a gate driver **530**.

A discharge diode **522** is coupled across the laser diode **518**. The discharge diode **522** is configured to allow an internal capacitance of the laser diode **518** to discharge when the transistor **520** is turned off. For example, the discharge diode **522** may have an anode and a cathode; the anode can be connected to the cathode of the laser diode **518**; the cathode can be connected to the anode of the laser diode **518**. As such, charge remaining on an internal capacitance of the laser diode **518** following a firing operation causes the discharge diode **522** to be forward biased, and the internal capacitance is allowed to discharge through the discharge diode **522**. Following such discharge, the discharge diode **522** is no longer forward biased.

To initiate firing, the gate driver **530** causes the transistor **520** to turn on by adjusting the voltage applied to the gate terminal **520***g*, which allows current to flow to the drain terminal **520***d* through the laser diode **518**. The capacitor **516** discharges through a discharge path that includes the laser diode **518** and the transistor **520**. The discharge current from the capacitor **516** causes the laser diode **518** to emit a pulse of light. The transistor **520** is turned back off by adjusting the voltage applied to the gate terminal **520***g* via the gate driver **530**. Upon turning off the transistor **520**, the laser diode **518** ceases emission.

The inductor **510** is connected between the voltage source **502** and the anode of the diode **514**. For convenience in the description and the drawings a point connecting the inductor **510** and the anode of the diode **514** is labeled node A **512**. The cathode of the diode **514** is connected to the capacitor **516** and also to the anode of the laser diode **518**. The capacitor's **516** charging path, which couples the capacitor **516** and the voltage source **502**, includes the inductor **510** and the diode **514**. During charging, the voltage across the inductor **510** varies in accordance with changes in the inductor current, and the diode **514** regulates the voltage applied to the capacitor **516** depending on whether the diode **514** is forward biased or reverse biased. The diode **514** is forward biased (and thus allows the capacitor **516** to charge) when the voltage at node A **512** is greater than the voltage on the capacitor **516**. The diode **514** is reverse based (and thus prevents the capacitor **516** from charging) when the voltage at node A **512** is less than the voltage on the capacitor **516**. Voltage variations at node A **512** due to changes in current through the inductor **510** may result in a voltage being applied to the capacitor **516** that exceeds the voltage of the voltage source **502**.

For example, the voltage source **502** connected to one side of the inductor **510** may have a voltage V_1. The voltage on the other side of the inductor **510**, at node A **512**, varies due to induced voltage across the inductor **510** as the inductor current changes. In particular, during a charging operation to recharge the capacitor **516**, the current through the inductor **510** briefly increases and then decreases. As the inductor current increases, the voltage at node A **512** may decrease to a voltage less than V_1. As the inductor current changes from increasing to decreasing, the voltage at node A **512** may increase to a higher level voltage (e.g., a voltage greater than V_1), before decreasing. The transient higher level voltage at node A **512** (e.g., $>V_1$) is applied to the capacitor **516**, which charges as the voltage at node A **512** decreases due to the inductor current continuing to decrease. The capacitor **516** charges until the voltage on the capacitor **516** approximately equal the voltage at node A **512**. Upon the voltage at node A **512** approximately equaling the voltage on the capacitor **516**, the diode **512** is reverse biased. Upon the diode **514** being reverse biased, the current through the inductor **510** goes to zero and the voltage across the inductor **510** settles at zero, which sets node A to the voltage of the voltage source **502** (e.g., the voltage V_1), but the capacitor **516** may hold a higher voltage (e.g., about 2 V_1).

The transistor **520** may be a field effect transistor (FET) with a channel region including Gallium nitride (i.e., the transistor **520** may be a GaNFET). However, alternative FETs may be employed, such as FETs configured to rapidly switch large current values, such as transistors with carrier mobility (e.g., high electron mobility transistors (HEMTs)). In FIG. **5**A, the transistor **520** is illustrated as a field effect transistor (FET); although it is understood the firing circuit **500** may be implemented with alternative transistors to selectively switch current through the laser diode, such as a bipolar junction transistor, etc. Further, while the transistor **520** is illustrated as an n-type transistor, a complementary circuit may be formed using a p-type transistor.

FIG. **5**B is a timing diagram of a pulse emission operation of the example laser diode firing circuit **500** of FIG. **5**A. Shown in FIG. **5**B is the gate voltage V_{Gate} of the FET **520**, the drain current I_{Drain} of the FET **520**, the luminosity L_{Diode} of the laser diode **518**, the voltage V_{Cap} of the capacitor **516**, the voltage V_A at node A **512**, the current I_{Ind} through the inductor **510**, and the light signal received Rx from a reflected portion of the emitted pulse. For convenience in the description, the time at which an initiating signal is applied to the transistor **520** and a pulse is emitted is referred to herein and in the drawings as the turn on time T_{ON}.

Initially, the capacitor **516** is charged to a voltage set in part by the voltage source **502**. The charge on the capacitor **516** may exceed the voltage V_1 of the voltage source **502** due to transient variations at node A **512** caused by changes in current through the inductor **510**. A voltage that exceeds V_1 may be held on the capacitor **516** after the diode **514** is reverse biased to terminate a charging operation. For example, the capacitor **516** may be initially charged to a voltage level of about 2 V_1. At the turn on time T_{ON}, an initiating signal is applied to the transistor **520** from the gate driver **530**. The initiating signal can be a gate voltage V_{Gate} that transitions from a low level to a high level so as turn on the transistor **520**. The transistor **520** turns on and the drain current I_{Drain} transitions from a current near zero to a current sufficient to drive the laser diode **518**. The laser diode **518** emits a pulse of light, as indicated by the luminosity L_{Diode}. As the drain current I_{Drain} flows through the laser diode **518**, the capacitor **516** discharges to source current to the laser diode **518**. In some examples, during pulse emission, the capacitor **516** and the parasitic capacitance of the laser diode **518** can combine to form a resonant LC tank circuit, which is heavily damped. Discharging the capacitor **516** thus transfers the electrical energy charged on the capacitor **516** to the laser diode **518**, where energy is consumed by current flowing in the laser diode to produce light. Upon completion of a single half-cycle of the damped LC oscillation, there may be almost no energy left to continue to drive current through the laser diode **518**, and remaining voltage, if any, can return to the capacitor **516** via the diode **522** connected in parallel across the laser diode **518**.

In practice then, the energy stored on the capacitor **516** may be consumed, and the laser diode **518** may turn off (at time T_{OFF}), following a single half-cycle of the resonant LC circuit formed by the capacitor **516** and the parasitic inductance of the inductor **518**. The pulse duration Δt_{ON} may be about 20 nanoseconds in some examples. In some cases (and as shown in FIG. **5**B), the laser diode **518** may cease emitting light prior to turning off the transistor **520** (e.g., by adjusting the gate voltage V_{Gate}). Although, in some examples, and depending on the values of the capacitor **516** and the parasitic inductance of the laser diode **518**, the pulse duration Δt_{ON} may continue until the transistor **520** turns off. Thus, in some examples, the transistor **520** can be turned off by adjusting the gate voltage V_{Gate} to a level sufficient to turn off the transistor **520**, which terminates current flowing through the laser diode **518**.

The charging cycle is initiated in response to the transistor **520** firing, which discharges the capacitor **516**. Upon the capacitor voltage V_{Cap} discharging to a voltage level sufficient to forward bias the diode **514**, at time T_1, current begins flowing through the inductor **510** (as indicated by I_{Ind} in FIG. **5**B). In FIG. **5**B, time T_1 is shown during the interval Δt_{ON} (i.e., before T_{OFF}), although in some implementations the diode **514** may not begin conducting current until the transistor **520** has turned off (i.e., after T_{OFF}). The increase in inductor current I_{Ind} causes the voltage at node A **512** to decrease in proportion to the time derivative of the inductor current I_{Ind}, because changes in the inductor current I_{Ind} induce a voltage in the inductor **510** that opposes the direction of any current change. The voltage at node A **512**, and thus the increasing inductor current I_{Ind}, are prevented from changing so rapidly as to reverse bias the diode **514**.

For example, starting at time T_1, the voltage at node A **512** may decrease to a voltage level less than V_1 (as indicated by V_A in FIG. **5**B). At time T_{OFF}, current ceases flowing through the laser diode **518**, and the diode **514** connects the inductor **510** and the capacitor **516**, which form a resonant LC tank circuit. The current from the inductor **510** charges the capacitor **516**, in a sinusoidal oscillatory fashion. At one quarter of the oscillation period, the inductor current I_{Ind} reaches a maximum, and begins to decrease. At that point, the resonant LC circuit divides its stored energy with about half in the capacitor **516** and about half in the inductor **510**. Continuing with the sinusoidal oscillation, current continues to flow to the capacitor **516**, until the mid-point of the oscillation cycle, at time T_2, at which point the current reaches zero and the capacitor **516** stores substantially all of the energy that had been divided between the inductor **510** and the capacitor **516**. Before the energy stored on the capacitor **516** can transfer back to the inductor **510**, the diode **514** becomes reverse biased, which causes the capacitor **516** to remain charged with approximately twice the supply voltage V_1. For example, the supply voltage V_1 may be about 20 volts and the voltage stored on the capacitor **516** following charging may be about 40 volts.

The oscillatory LC circuit described herein efficiently transfers energy between the inductor **510** and the capacitor **516** during the recharge interval Δt_{CHARGE} of the circuit **500**, but the present disclosure is not limited to the use of resonant LC circuits. Generally, the capacitor **516** may be charged to a greater value than the supply voltage V1 based on transient voltages on the inductor **510** caused by changes in current following firing of the circuit **500**. Current through the inductor **510** may change from increasing (e.g., between times T_1 and T_{OFF}) to decreasing (e.g., following time T_{OFF}), and the sudden change in current through the inductor **510** can induce a rapid increase in voltage at node A **512**. For example, at time T_{OFF}, the voltage at node A **512** can go to a voltage greater than V_1, and may be several times V_1. The precise voltage applied to node A **512** depends on the time derivative of the inductor current when transitioning from an increasing current to a decreasing current, but may be several times the voltage of the voltage source **502** (e.g., just after T_{OFF}, $V_A \approx X\ V_1$, with $X>2$).

Following the increase in the voltage at node A **512**, the current through the inductor **510** can continue to decrease as the capacitor **516** becomes charged, and the voltage at node A **512** can therefore decrease. The capacitor **516** may continue charging until the diode **514** becomes reverse biased, at time T_2 in FIG. **5**B. While charging, between times T_{OFF} and T_2, the voltage V_{Cap} across the capacitor **516** increases and the

voltage V_A of node A **512** decreases. The time T_2, at which the charging cycle stops, occurs when the two voltages approximately equal one another (e.g., $V_A \approx V_{Cap}$). In some examples, the voltage at which the two voltages are approximately equal so as to terminate the charging cycle occurs for a voltage of about 2 V_1 (e.g., 2 $V_1 \approx V_A \approx V_{Cap}$). The voltage on the capacitor **516** (i.e., V_{Cap}) following the charging cycle may be, for example, about 40 Volts. Upon the diode **514** becoming reverse biased, at time T_2, the charging current stops flowing through the diode **514**, and therefore the current I_{Ind} through the inductor **518** changes quickly to zero. The change in inductor current at time T_2 is therefore accompanied a change in the voltage V_A of node A, to return to the voltage of the voltage source **502** (i.e., the voltage V_1).

The voltage variations across the inductor **510** can be described in terms of energy temporarily stored in a magnetic field of the inductor **510** and then released. Energy stored in an inductor's magnetic field is proportionate to the square of the current flowing through the inductor. When the inductor current I_{Ind} is increased, the inductor **510** increases the energy stored in its magnetic field (e.g., according to the difference in current I_{Ind}). Increasing the inductor current I_{Ind} thus charges the energy stored in the magnetic field of the inductor **510** from a low energy level (e.g., zero) to a high energy level. When the inductor **510** is being charged by an increasing current from the voltage source **502**, the induced voltage across the inductor **510** opposes the change in current and so node A **512** goes to a voltage less than V_1. By contrast, when the inductor current I_{Ind} is decreased, the energy stored in the magnetic field of the inductor **510** is decreased. Decreasing the inductor current I_{Ind} thus discharges the energy stored in the magnetic field of the inductor **510** from high energy level to a low energy level. When the inductor **510** is being discharged by a decreasing current from the voltage source **502**, the induced voltage across the inductor **510** opposes the change in current and so node A **512** goes to a voltage higher than V_1. However, the diode **514** only remains forward biased while the voltage at node A **512** exceeds the voltage across the capacitor **516**.

The diode **514** and inductor **510** can thus combine to cause the capacitor **516** to be charged to a voltage that exceeds the voltage V_1 of the voltage source **502**. For example, the diode **514** is forward biased when the voltage across the capacitor **516** is at a lower level, such as between time times T_{OFF} and T_2 as shown in FIG. **5**B when the capacitor voltage V_{Cap} charges from less than V_1 to about 2 V_1. However, the diode **514** is reverse biased when the voltage across the capacitor **516** is at a higher level, such as following time T_2 as shown in FIG. **5**B when the capacitor voltage V_{Cap} remains at about 2 V_1 while the voltage V_A at node A **512** decreases to V_1. For example, V_1 may be about 20 Volts and the capacitor voltage V_{Cap} following charging may be about 40 Volts.

In some examples, the firing circuit **500** is operated such that the capacitor **516** is recharged immediately following emission of a pulse of light from the laser diode **518**. As shown in FIG. **5**B, a capacitor recharging interval Δt_{CHARGE} begins at the transistor turn off time T_{OFF} and ends with the reverse biasing of the diode **514**, at time T_2. The capacitor recharging interval Δt_{CHARGE} may be approximately 500 nanoseconds, for example. Moreover, by configuring the firing circuit **500** such that the capacitor **516** is recharged immediately following a pulse emission, the firing circuit **500** can be recharged and ready to emit a subsequent pulse faster than an alternative configuration. If, for example, a recharging operation were to be initiated after some duration following a pulse emission (e.g., using a second transistor other than a transistor controlling current through a laser diode), the additional time would increase the lag time between emission of subsequent pulses and thus reduce the duty cycle of the firing circuit. In some examples, the firing circuit **500** is configured to immediately recharge the capacitor **516** upon emission of a pulse because the recharging operation is initiated in response to operation of the same transistor **520** that initiates emission (e.g., turning on the transistor **520** both causes a pulse to be emitted and, upon sufficient discharge from the capacitor **516**, causes the diode **514** to become forward biased and current to begin flowing through the inductor **510** so as to initiate charging).

The light pulse emitted at time T_{ON} can be reflected from an environmental object, such as an obstacle surrounding an autonomous vehicle, and a light signal from the reflected portion of the emitted pulse is received via a photo detector at reception time T_{Rx}. The time ΔT between the emission time (at time T_{ON}) and the reception time T can then be used to calculate the distance to the reflective object. For example, the round trip travel time ΔT can be multiplied by the speed of light in the surrounding atmosphere to get the round trip distance, which is twice the distance to the reflective object.

In some examples, the emission time of the emitted pulse may be determined using a feedback loop configured to react to the discharge current flowing through the laser diode **518**. For example, a conductive loop may be situated such that a voltage is induced in the loop due to changing magnetic flux through the loop in response to the discharge current flowing through the firing circuit **500**. The voltage across the leads of such a conductive feedback loop can then be detected, and the time at which a pulse is emitted from the firing circuit can be estimated based on the time the voltage is detected. Such a system can be used to reduce timing uncertainty in the firing time due to delays between application of the turn on signal (e.g., the gate voltage V_{Gate}) and the firing of the laser diode **518**, which may involve some non-zero random and/or systematic timing delay and/or timing jitter.

FIG. **5**C shows a current path through the example laser diode firing circuit **500** of FIG. **5**A during a charging mode. During charging, the voltage across the capacitor **516** is less than the voltage at the node between the inductor **510** and diode **514** such that the diode **514** is forward biased. In addition, the transistor **520** is turned off (as indicated by the OFF block coupled to the gate terminal **520***g* in FIG. **5**C). As such, current does not flow through the laser diode **518**, and instead flows to accumulate charge across the capacitor **516**. The dashed arrow in FIG. **5**C illustrates such a charging current path, which flows from the voltage source **502** (which may have a voltage V_1), through the biasing diode **514**, toward the capacitor **516**. In some examples, following a discharge, the capacitor **516** can be recharged in preparation for a subsequent discharge (and associated pulse emission) event in about 500 nanoseconds.

FIG. **5**D shows a current path through the example laser diode firing circuit **500** of FIG. **5**A during an emission mode. During emission, the transistor **520** is turned on (as indicated by the ON block coupled to the gate terminal **520***g* in FIG. **5**D). As such, the capacitor **516** is connected across the laser diode **518** (via the turned on transistor **520**), and so the charge on the capacitor **516** rapidly discharges through the laser diode **518** and the transistor **520**. The dashed arrow in FIG. **5**D illustrates such a discharge current path, which flows from the capacitor **516**, through the laser diode **518** and the transistor **520** toward ground. Upon the transistor **520** being turned on, the discharge current flows rapidly to discharge the capacitor **516** and the resulting change in current (e.g., increase in current) causes the laser diode **518** to emit a pulse of light.

The current paths shown in FIGS. **5**C and **5**D illustrate two operation modes of the firing circuit **500**: a charging mode (FIG. **5**C) and an emission mode (FIG. **5**D). In some examples, the firing circuit **500** switches between the charging mode and the emission mode based solely on whether the transistor **520** is turned on or turned off. In the charging mode, the transistor **520** is turned off and current flows from the voltage source **502** to the capacitor **516** via the charging path (e.g., the current path including the inductor **510** and diode **514**) until the diode **514** is reverse biased. In the emission mode, the transistor **520** is turned on and current flows from the charged capacitor **516** through the laser diode **518** and the transistor **520** until the transistor **520** is turned off again.

FIG. **5**E illustrates an arrangement **540** in which multiple laser diode firing circuits **550***a-n* are connected to be charged via a single inductor **544**. The inductor **544** has one terminal connected to a voltage source **542** (labeled V_1), and a second terminal that connects to the firing circuits **550***a-n* so as to be included in a charging path of the respective firing circuits **550***a-n*. Each of the firing circuits **550***a-n* can be similar to the firing circuit **500** described above in connection with FIGS. **5**A-**5**D. For example, the first firing circuit **550***a* includes a capacitor **558***a* connected to a laser diode **554***a* and a transistor **556***a*. The capacitor **558***a*, laser diode **554***a*, and transistor **556***a* can be connected in series such that turning on the transistor **556***a* causes the capacitor **558***a* to discharge through the laser diode **554***a*, which causes the laser diode to emit a pulse of light. A discharge diode **560***a* can be connected across the laser diode **554***a* to discharge the internal capacitance of the laser diode **554***a*. The first firing circuit **550***a* also includes a diode **552***a* that connects the firing circuit **550***a* to the inductor **544** and the voltage source **542**. The diode **552***a* can function similarly to the diode **514** described above in connection with FIGS. **5**A-**5**D. For example, the diode **552***a* can become forward biased and draw current through the inductor **544** to charge the capacitor **558***a* following a firing event (and associated discharge of the capacitor **558***a*). Upon the capacitor **558***a* being recharged, the diode **552***a* can then become reverse biased and thereby cause the capacitor **558***a* to maintain its stored charge.

The second firing circuit **550***b* is similarly connected to the inductor **544** via a diode **552***b* and includes a capacitor **558***b*, laser diode **554***b*, transistor **556***b*, discharge diode **560***b*. One or more additional firing circuits can also be similarly connected in parallel with the inductor **544** to the "nth" firing circuit **550***n*. In some cases, the arrangement **540** includes 16 individual laser diode firing circuits **550***a-n* connected to the single inductor **544**.

Similar to the operation of the firing circuit described above in connection with FIGS. **5**A-**5**D, the firing circuits **550***a-n* are turned on and off by operation of their respective transistors **556***a-n*, which are controlled by the respective gate voltages applied by the gate driver **548**. For example, the gate driver **548** can be used to turn on all of the firing circuits **550***a-n* at substantially the same time by setting the gate voltage high (or otherwise manipulating the gate voltage to turn the respective transistors on). The discharging capacitors **558***a-n* cause current to begin flowing through the inductor **544**. Upon the transistors **556***a-n* in the firing circuits **550***a-n* being turned back off (by the gate driver **548**), the voltage across the inductor rises to begin recharging the capacitors **558***a-n* in the firing circuits **550***a-n* until the respective diodes **552***a-n* are reverse biased, at which point recharging terminates.

Additionally, the firing circuit arrangement **540** shown in FIG. **5**E also illustrates a snubber circuit **546** connected across the inductor **544**. The snubber circuit **546** provides an alternative current path during rapid current switching through the inductor **544** to regulate and/or smooth the resulting variations across the inductor **544**. The snubber circuit **546** may include a resistor and/or capacitor connected in parallel across the inductor **544**, for example. The snubber circuit **546** may additionally or alternatively include one or more diodes and/or solid state components configured to limit and/or regulate the maximum voltage and/or maximum voltage rate across the inductor **544**. Thus, the snubber circuit **546** may operate actively and/or passively to modify transient voltage variations across the inductor **544**. In some cases, the snubber circuit **544** may be used to prevent transient voltage variations from exceeding a predetermined threshold and thereby prevent damage to circuit components. While illustrated in FIG. **5**E, the snubber circuit **544** may (or may not) be included in particular implementations of the arrangement **540** shown in FIG. **5**E. Moreover, a snubber circuit may (or may not) be included across the charging path inductor in a particular implementation of the single firing circuit arrangement described above in connection with FIG. **5**A-**5**D.

V. Example Operations

FIGS. **6**A through **6**C present flowcharts describing processes employed separately or in combination in some embodiments of the present disclosure. The methods and processes described herein are generally described by way of example as being carried out by an autonomous vehicle, such as the autonomous vehicles **100**, **200** described above in connection with FIGS. **1** and **2**. For example, the processes described herein can be carried out by the LIDAR sensor **128** mounted to an autonomous vehicle in communication with the computer system **112**, sensor fusion algorithm module **138**, and/or computer vision system **140**.

Furthermore, it is noted that the functionality described in connection with the flowcharts described herein can be implemented as special-function and/or configured general-function hardware modules, portions of program code executed by a processor (e.g., the processor **113** in the computer system **112**) for achieving specific logical functions, determinations, and/or steps described in connection with the flowcharts. Where used, program code can be stored on any type of computer readable medium (e.g., computer readable storage medium or non-transitory media, such as data storage **114** described above with respect to computer system **112**), for example, such as a storage device including a disk or hard drive. In addition, each block of the flowcharts can represent circuitry that is wired to perform the specific logical functions in the process. Unless specifically indicated, functions in the flowcharts can be executed out of order from that shown or discussed, including substantially concurrent execution of separately described functions, or even in reverse order in some examples, depending on the functionality involved, so long as the overall functionality of the described method is maintained. Furthermore, similar combinations of hardware and/or software elements can be employed to implement the methods described in connection with other flowcharts provided in the present disclosure.

FIG. **6**A is a flowchart of an example process **600** for operating a laser diode firing circuit. The laser diode firing circuit may be the laser diode firing circuit **500** described above in connection with FIG. **5**. The laser diode firing circuit may therefore include a capacitor connected to a charging path and a discharge path. The discharge path can include a laser diode and a transistor, and the charging path can include an inductor and a diode. At block **602**, the transistor is turned off, which causes the capacitor to charge via the charging

path. The current through the charging path can flow through the inductor and the diode. As charge builds on the capacitor, the current through charging path (and the inductor) decreases. The decrease in current through the inductor causes the inductor to discharge energy stored in its magnetic field. For example, the energy stored in the magnetic field of the inductor may transition from a higher energy level to a lower energy level in response to the transistor being turned off. At block **604**, the transistor can be turned on, which causes the capacitor to discharge via the discharge path. The current through the discharge path can flow through the laser diode and the transistor, which causes the laser diode to emit a pulse of light. The voltage stored on the capacitor can discharge until the diode is forward biased, which causes the current through the charging path (and the inductor) to increase. The increase in current through the inductor causes the inductor to charge energy stored in its magnetic field. For example, the energy stored in the magnetic field of the inductor may transition from a lower energy level to a higher energy level in response to the transistor being turned on.

In some embodiments, the operation of the transistor in blocks **602** and **604** provides for operation of a laser diode firing circuit to emit pulses of light and recharge by manipulating only a single transistor. In particular, turning the transistor on (block **604**) can cause the circuit to both emit a pulse of light (by discharging the capacitor through the laser diode) and initiate a recharge cycle (by the voltage on the capacitor discharging to a level sufficient to forward bias the diode in the charging path). The recharge cycle is then terminated in response to turning off the transistor (block **602**), which directs the current conveyed via the charging path to the capacitor (rather than through the laser diode).

FIG. **6**B is a flowchart of an example process **620** for operating a light detection and ranging (LIDAR) device. The LIDAR device includes a light source having a laser diode firing circuit similar to the firing circuit **500** described above in connection with FIG. **5**. For example, the laser diode firing circuit may include a laser diode activated by current through a discharge path of a capacitor. A transistor in the discharge path is configured to control such discharge events by turning on and turning off. The capacitor is also connected to a charging path that includes an inductor and a diode. The transistor may be, for example, a Gallium nitride field effect transistor (GaNFET). At block **622**, the GaNFET is turned off to thereby cause the capacitor to charge (via the charging path) and the inductor (in the charging path) to decrease its stored energy. The inductor can release stored energy as current through the inductor decreases. At block **624**, the GaNFET is turned on to thereby cause the capacitor to discharge (via the discharge path), which causes the laser diode to emit a pulse of light. The inductor charges to an increased stored energy level due to increasing current through the inductor, which occurs once the diode is forward biased. At block **626**, the transmission time of the emitted pulse (e.g., the pulse emission time) is determined. The pulse emission time may be determined based on the time at which the transistor is turned on to initiate the discharge current and/or based on the time an induced voltage is detected in a conductive feedback loop configured to react to changes in the discharge current path. At block **628**, a reflected light pulse is received. The reflected light pulse can include at least a portion of the light pulse emitted in block **624** that is reflected from a reflective object in an environment surrounding the LIDAR device. At block **630**, a reception time of the reflected light pulse is determined. At block **632**, a distance to the reflective object is determined based on both the time of reception determined in block **630** of the reflected light signal and the transmission time determined in block **624**. For example, the distance can be determined based on computing the round trip travel time to the reflective object from the difference of the reception time and emission time, multiplying by the speed of light in the surrounding environment and dividing by 2. At block **634**, the autonomous vehicle is navigated based at least in part on the determined distance to the reflective object. In some examples, one or more of the control systems **106** of the autonomous vehicle **100** described in connection with FIG. **1** may control the autonomous vehicle to avoid obstacles (e.g., the reflective object), navigate toward a predetermined destination, etc.

FIG. **6**C is a flowchart of another example process **640** for operating a laser diode firing circuit. The laser diode firing circuit may be similar to the firing circuit **500** described above in connection with FIG. **5**. For example, the laser diode firing circuit may include a laser diode activated by current through a discharge path of a capacitor. A transistor in the discharge path is configured to control such discharge events by turning on and turning off. The capacitor is also connected to a charging path that includes an inductor and a diode. The transistor may be, for example, a Gallium nitride field effect transistor (GaNFET). At block **642**, the GaNFET is turned on. At block **644**, the capacitor discharges through the discharge path. At block **646**, a pulse of light is emitted from the laser diode due to the discharge current. At block **648**, energy stored in the inductor included in the charging path is increased. For example, upon the diode in the charging path becoming forward biased, the current through the inductor can be increased, which causes energy to be stored in the magnetic field of the inductor. At block **650**, the GaNFET is turned off. At block **652**, energy stored in the inductor is released as the inductor current decreases. At block **654**, the capacitor is charged from energy released by the inductor. For example, following turning off the GaNFET, current through the inductor is conveyed to the capacitor via the charging path. The inductor current can transition from increasing (while the transistor is on) to decreasing (once the transistor is off and current no longer flows through the laser diode). The decrease in inductor current causes the inductor to release its stored energy, and that released energy can be transferred, at least in part, to the capacitor. At block **656**, the charging path diode can become reverse biased, which causes the capacitor to hold charge due to the released energy from the inductor. For example, while the inductor releases its stored energy, the voltage conveyed to the capacitor via the diode can transiently exceed the voltage of the voltage source connected to the inductor. The capacitor charges until the capacitor voltage approximately equals the voltage applied to the diode, at which point the diode is reverse biased. The capacitor holds a voltage due in part to the transient voltage while the voltage applied to the diode settles to the voltage of the voltage source (e.g., upon the inductor current reaching zero).

As indicated by the dashed arrow in FIG. **6**C, the process **640** can be repeated to cause the firing circuit to repeatedly emit pulses of light, and be recharged immediately following each firing event. Moreover, the firing circuit may be operated such that the voltage charged on the capacitor following a given firing event is not sufficient to forward bias the diode in the charging path. In such an example, the firing circuit is not recharged and the firing circuit is re-activated by discharging the charge remaining on the capacitor to generate current through the laser diode and transistor. If the voltage on the capacitor discharges to a level sufficient to forward bias the diode in the charging current path following such a second

firing (or third firing, etc.), the firing circuit can then undergo the charging mode with the capacitor recharging via the charging path.

FIG. **7** depicts a computer-readable medium configured according to an example embodiment. In example embodiments, the example system can include one or more processors, one or more forms of memory, one or more input devices/interfaces, one or more output devices/interfaces, and machine-readable instructions that when executed by the one or more processors cause the system to carry out the various functions, tasks, capabilities, etc., described above, such as the processes discussed in connection with FIGS. **6**A through **6**C above.

As noted above, in some embodiments, the disclosed techniques can be implemented by computer program instructions encoded on a non-transitory computer-readable storage media in a machine-readable format, or on other non-transitory media or articles of manufacture (e.g., the instructions **115** stored on the data storage **114** of the computer system **112** of vehicle **100**). FIG. **7** is a schematic illustrating a conceptual partial view of an example computer program product **700** that includes a computer program for executing a computer process on a computing device, arranged according to at least some embodiments presented herein.

In one embodiment, the example computer program product **700** is provided using a signal bearing medium **702**. The signal bearing medium **702** may include one or more programming instructions **704** that, when executed by one or more processors may provide functionality or portions of the functionality described above with respect to FIGS. **1-6**. In some examples, the signal bearing medium **702** can be a non-transitory computer-readable medium **706**, such as, but not limited to, a hard disk drive, a Compact Disc (CD), a Digital Video Disk (DVD), a digital tape, memory, etc. In some implementations, the signal bearing medium **702** can be a computer recordable medium **708**, such as, but not limited to, memory, read/write (R/W) CDs, R/W DVDs, etc. In some implementations, the signal bearing medium **702** can be a communications medium **710**, such as, but not limited to, a digital and/or an analog communication medium (e.g., a fiber optic cable, a waveguide, a wired communications link, a wireless communication link, etc.). Thus, for example, the signal bearing medium **702** can be conveyed by a wireless form of the communications medium **710**.

The one or more programming instructions **704** can be, for example, computer executable and/or logic implemented instructions. In some examples, a computing device such as the computer system **112** of FIG. **1** is configured to provide various operations, functions, or actions in response to the programming instructions **704** conveyed to the computer system **112** by one or more of the computer readable medium **706**, the computer recordable medium **708**, and/or the communications medium **710**.

The non-transitory computer readable medium could also be distributed among multiple data storage elements, which could be remotely located from each other. The computing device that executes some or all of the stored instructions could be a vehicle, such as the vehicle **200** illustrated in FIG. **2**. Alternatively, the computing device that executes some or all of the stored instructions could be another computing device, such as a server.

While various example aspects and example embodiments have been disclosed herein, other aspects and embodiments will be apparent to those skilled in the art. The various example aspects and example embodiments disclosed herein are for purposes of illustration and are not intended to be limiting, with the true scope and spirit being indicated by the following claims.

What is claimed is:

1. An apparatus, comprising:

a voltage source;

an inductor coupled to the voltage source, wherein the inductor is configured to store energy in a magnetic field;

a diode coupled to the voltage source via the inductor;

a transistor configured to be turned on and turned off by a control signal;

a light emitting element coupled to the transistor;

a capacitor coupled to a charging path and a discharge path, wherein the charging path includes the inductor and the diode, and wherein the discharge path includes the transistor and the light emitting element;

wherein, responsive to the transistor being turned off, the capacitor is configured to charge via the charging path such that a voltage across the capacitor increases from a lower voltage level to a higher voltage level and the inductor is configured to release energy stored in the magnetic field such that a current through the inductor decreases from a higher current level to a lower current level; and

wherein, responsive to the transistor being turned on, the capacitor is configured to discharge through the discharge path such that the light emitting element emits a pulse of light and the voltage across the capacitor decreases from the higher voltage level to the lower voltage level and the inductor is configured to store energy in the magnetic field such that the current through the inductor increases from the lower current level to the higher current level.

2. The apparatus of claim **1**, wherein the lower current level is approximately zero.

3. The apparatus of claim **1**, wherein the capacitor is charged immediately following emission of a pulse of light from the light emitting element.

4. The apparatus of claim **1**, wherein the higher voltage level is greater than a voltage of the voltage source, and wherein the diode has an anode coupled to the voltage source via the inductor and a cathode coupled to the capacitor, such that the diode is forward biased when the voltage across the capacitor is at the lower voltage level and the diode is reverse biased when the voltage across the capacitor is at the higher voltage level.

5. The apparatus of claim **1**, wherein the transistor is a Gallium nitride field effect transistor (GaNFET).

6. The apparatus of claim **5**, wherein the control signal applies voltage to a gate of the GaNFET to selectively turn the GaNFET on and off.

7. The apparatus of claim **1**, wherein the light emitting element is a laser diode.

8. The apparatus of claim **7**, further comprising a drain diode coupled across the laser diode, wherein the drain diode is configured to discharge an internal capacitance of the laser diode through the drain diode when the transistor is off.

9. A method, comprising:

turning off a transistor, wherein the transistor is coupled to a light emitting element, wherein both the transistor and the light emitting element are included in a discharge path coupled to a capacitor, wherein the capacitor is also coupled to a charging path including a diode and an inductor, wherein the inductor is configured to store energy in a magnetic field, wherein the diode is coupled to a voltage source via the inductor, and wherein, responsive to the transistor being turned off, the capaci-

tor is configured to charge via the charging path such that a voltage across the capacitor increases from a lower voltage level to a higher voltage level and the inductor is configured to release energy stored in the magnetic field such that a current through the inductor decreases from a higher current level to a lower current level; and

turning on the transistor, wherein responsive to the transistor being turned on, the capacitor is configured to discharge through the discharge path such that the light emitting element emits a pulse of light and the voltage across the capacitor decreases from the higher voltage level to the lower voltage level and the inductor is configured to store energy in the magnetic field such that the current through the inductor increases from the lower current level to the higher current level.

10. The method of claim **9**, wherein the lower current level is approximately zero.

11. The method of claim **9**, wherein the capacitor is charged immediately following emission of a pulse of light from the light emitting element.

12. The method of claim **9**, wherein the higher voltage level is greater than a voltage of the voltage source, and wherein the diode has an anode coupled to the voltage source via the inductor and a cathode coupled to the capacitor, such that the diode is forward biased when the voltage across the capacitor is at the lower voltage level and the diode is reverse biased when the voltage across the capacitor is at the higher voltage level.

13. The method of claim **9**, wherein the charging of the capacitor is carried out in about 500 nanoseconds.

14. The method of claim **9**, wherein the light emitting element is a laser diode.

15. The method of claim **14**, further comprising:

when the transistor is off, discharging an internal capacitance of the laser diode via a drain diode coupled across the laser diode.

16. The method of claim **9**, wherein the transistor comprises a Gallium nitride field effect transistor (GaNFET), wherein the GaNFET is turned on and turned off by applying a control signal to a gate of the GaNFET.

17. A light detection and ranging (LIDAR) device comprising:

a light source including:

a voltage source;

an inductor coupled to the voltage source, wherein the inductor is configured to store energy in a magnetic field;

a diode coupled to the voltage source via the inductor;

a transistor configured to be turned on and turned off by a control signal;

a light emitting element coupled to the transistor;

a capacitor coupled to a charging path and a discharge path, wherein the charging path includes the inductor and the diode, and wherein the discharge path includes the transistor and the light emitting element;

wherein, responsive to the transistor being turned off, the capacitor is configured to charge via the charging path such that a voltage across the capacitor increases from a lower voltage level to a higher voltage level and the inductor is configured to release energy stored in the magnetic field such that a current through the inductor decreases from a higher current level to a lower current level; and

wherein, responsive to the transistor being turned on, the capacitor is configured to discharge through the discharge path such that the light emitting element emits a pulse of light and the voltage across the capacitor decreases from the higher voltage level to the lower voltage level and the inductor is configured to store energy in the magnetic field such that the current through the inductor increases from the lower current level to the higher current level;

a light sensor configured to detect a reflected light signal comprising light from the emitted light pulse reflected by a reflective object; and

a controller configured to determine a distance to the reflective object based on the reflected light signal.

18. The LIDAR device of claim **17**, wherein the lower current level is approximately zero.

19. The LIDAR device of claim **17**, wherein the capacitor is charged immediately following emission of a pulse of light from the light emitting element.

20. The LIDAR device of claim **17**, wherein the transistor is a Gallium nitride field effect transistor (GaNFET).

* * * * *

EXHIBIT C

US009086273B1

(12) **United States Patent**
Gruver et al.

(10) **Patent No.: US 9,086,273 B1**
(45) **Date of Patent: Jul. 21, 2015**

(54) **MICROROD COMPRESSION OF LASER BEAM IN COMBINATION WITH TRANSMIT LENS**

(71) Applicant: **Google Inc.**, Mountain View, CA (US)

(72) Inventors: **Daniel Gruver**, San Francisco, CA (US); **Pierre-Yves Droz**, Mountain View, CA (US); **Gaetan Pennecot**, San Francisco, CA (US); **Zachary Morriss**, San Francisco, CA (US); **Dorel Ionut Iordache**, Walnut Creek, CA (US)

(73) Assignee: **Google Inc.**, Mountain View, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 20 days.

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(22) Filed: **Mar. 8, 2013**

(51) **Int. Cl.**
G01C 3/08 (2006.01)
G01C 3/02 (2006.01)

(52) **U.S. Cl.**
CPC ***G01C 3/02*** (2013.01)

(58) **Field of Classification Search**
CPC G01S 17/10; G01S 7/497; G01S 17/89; G01S 7/487; G01C 3/08
USPC 356/3.01, 4.01, 4.07, 5.01, 5.09, 9, 625
See application file for complete search history.

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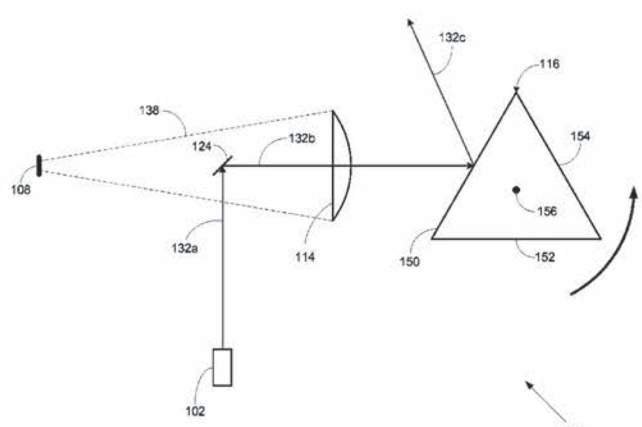
Primary Examiner — Isam Alsomiri
Assistant Examiner — Samantha K Abraham
(74) *Attorney, Agent, or Firm* — McDonnell Boehnen Hulbert & Berghoff LLP

(57) **ABSTRACT**

A LIDAR device may transmit light pulses originating from one or more light sources and may receive reflected light pulses that are detected by one or more detectors. The LIDAR device may include a lens that both (i) collimates the light from the one or more light sources to provide collimated light for transmission into an environment of the LIDAR device and (ii) focuses the reflected light onto the one or more detectors. Each light source may include a respective laser diode and cylindrical lens. The laser diode may emit an uncollimated laser beam that diverges more in a first direction than in a second direction. The cylindrical lens may pre-collimate the uncollimated laser beam in the first direction to provide a partially collimated laser that diverges more in the second direction than in the first direction.

20 Claims, 6 Drawing Sheets



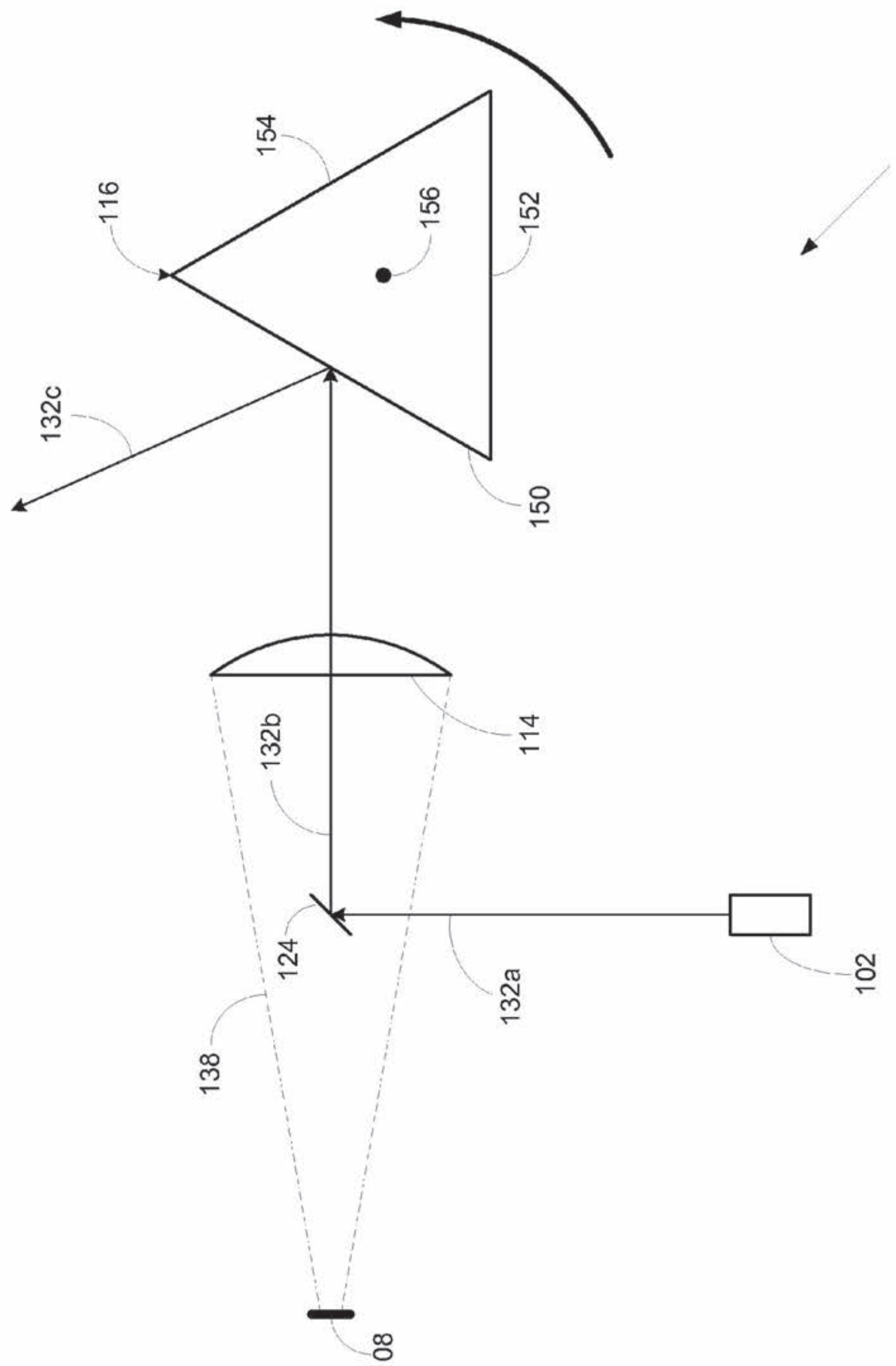


Figure 1A

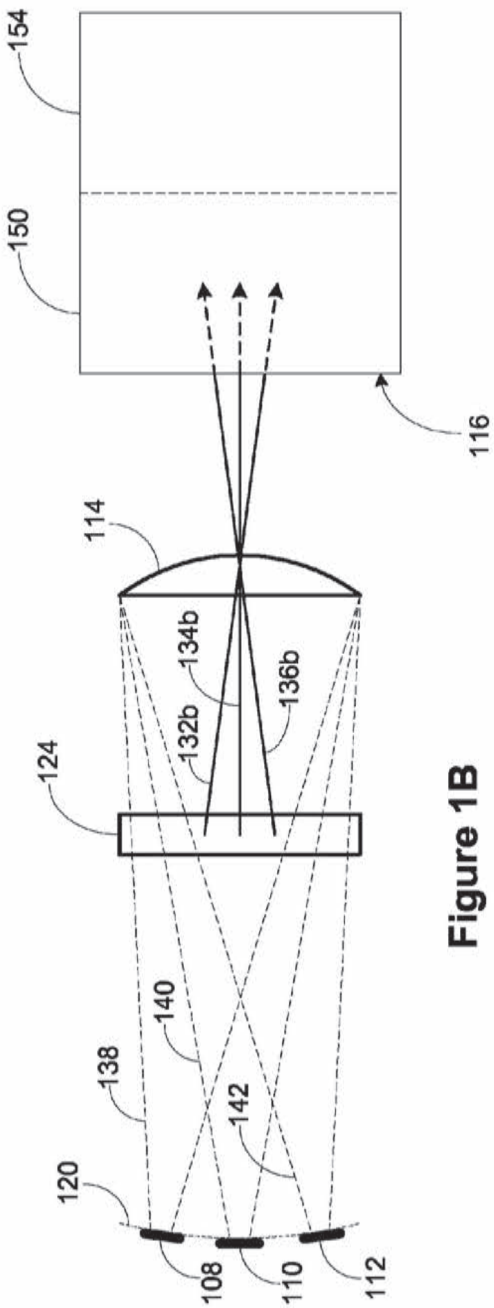


Figure 1B

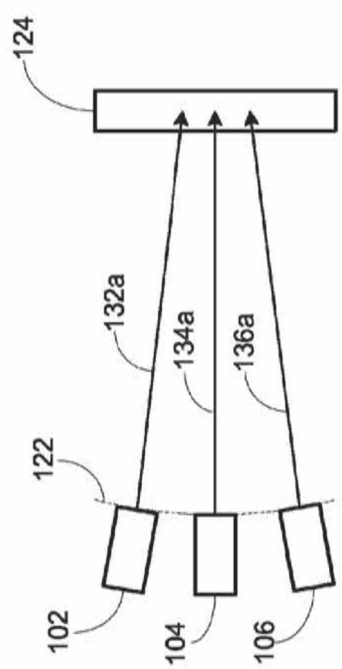


Figure 1C

FIG. 2A

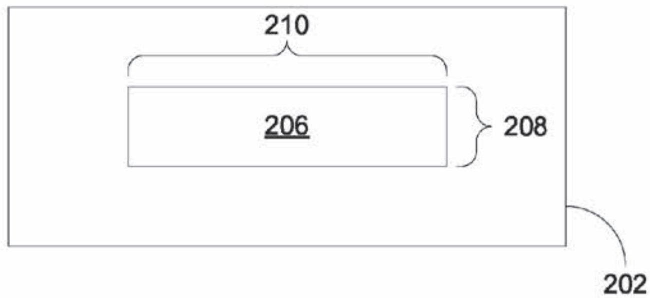


FIG. 2B

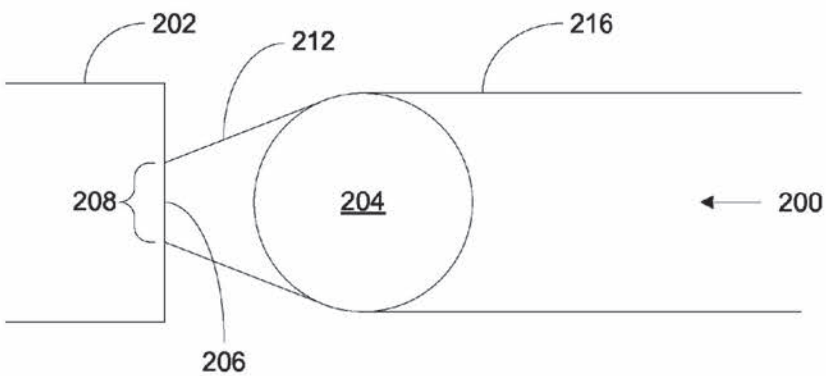
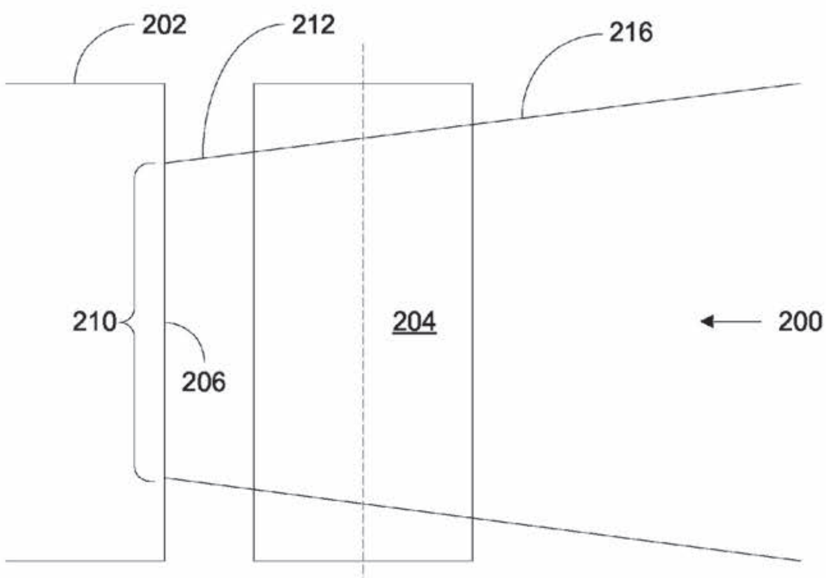


FIG. 2C



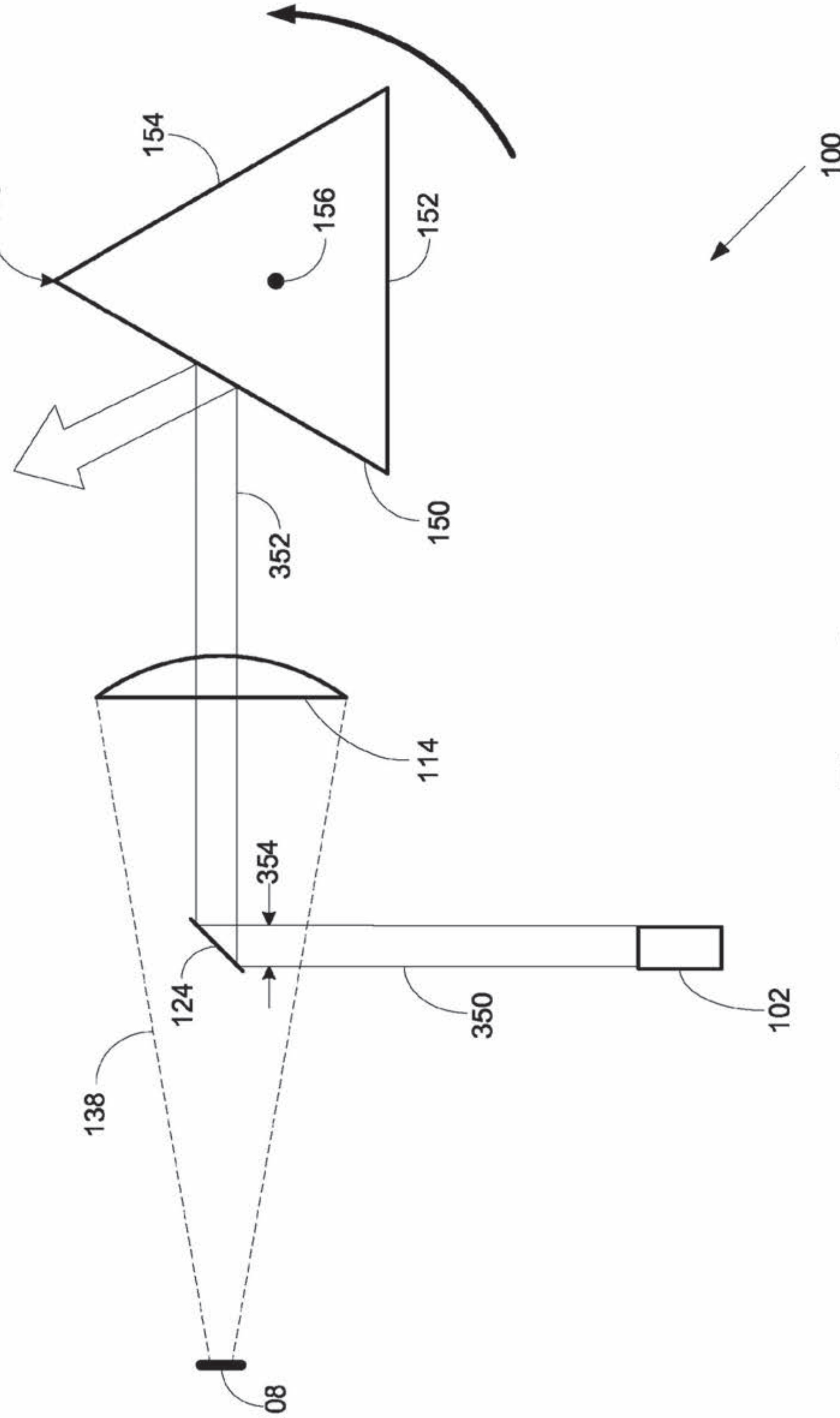


Figure 3

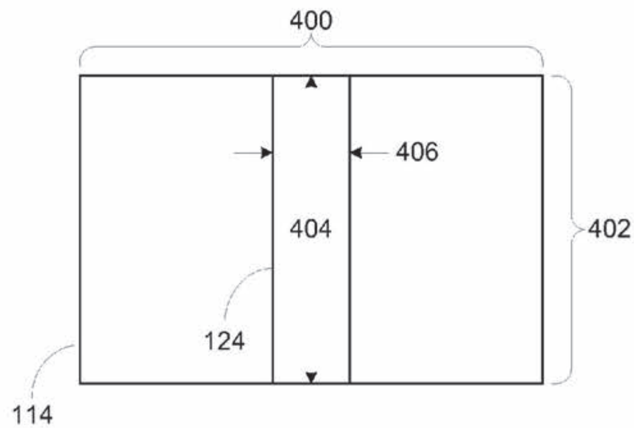


Figure 4

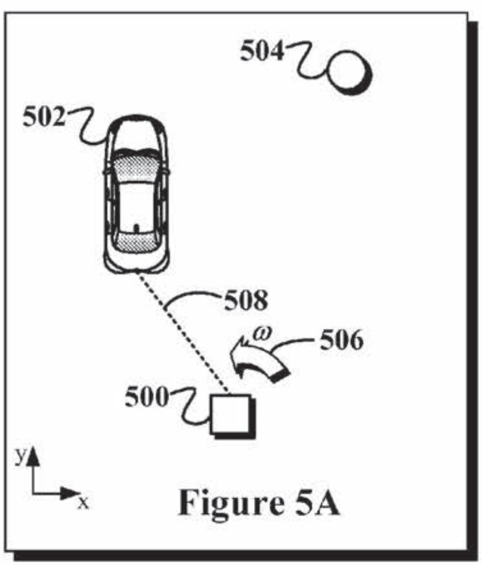


Figure 5A

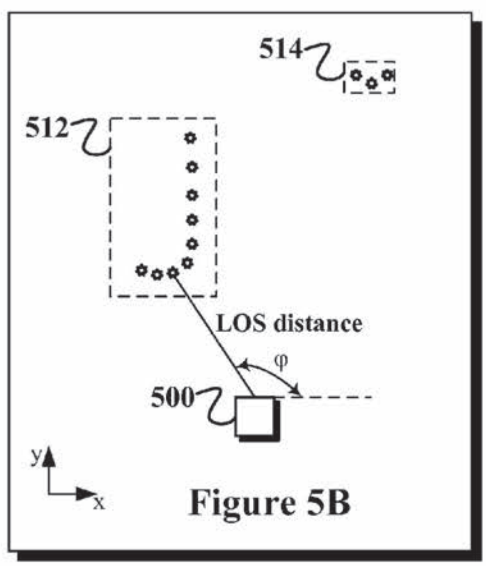


Figure 5B

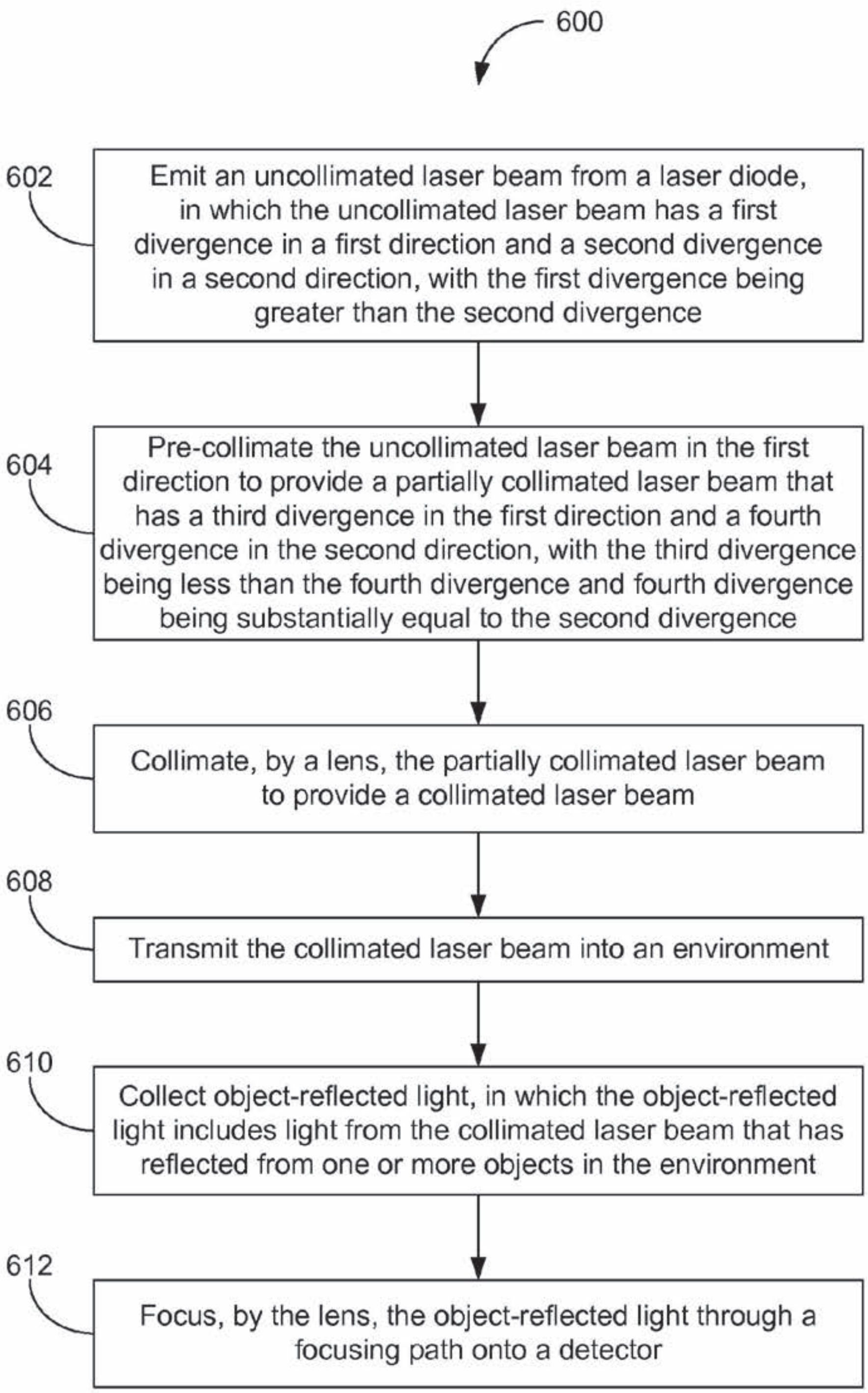

600
602
Emit an uncollimated laser beam from a laser diode, in which the uncollimated laser beam has a first divergence in a first direction and a second divergence in a second direction, with the first divergence being greater than the second divergence
604
Pre-collimate the uncollimated laser beam in the first direction to provide a partially collimated laser beam that has a third divergence in the first direction and a fourth divergence in the second direction, with the third divergence being less than the fourth divergence and fourth divergence being substantially equal to the second divergence
606
Collimate, by a lens, the partially collimated laser beam to provide a collimated laser beam
608
Transmit the collimated laser beam into an environment
610
Collect object-reflected light, in which the object-reflected light includes light from the collimated laser beam that has reflected from one or more objects in the environment
612
Focus, by the lens, the object-reflected light through a focusing path onto a detector

Figure 6

MICROROD COMPRESSION OF LASER BEAM IN COMBINATION WITH TRANSMIT LENS

BACKGROUND

Unless otherwise indicated herein, the materials described in this section are not prior art to the claims in this application and are not admitted to be prior art by inclusion in this section.

Vehicles can be configured to operate in an autonomous mode in which the vehicle navigates through an environment with little or no input from a driver. Such autonomous vehicles can include one or more sensors that are configured to detect information about the environment in which the vehicle operates. The vehicle and its associated computer-implemented controller use the detected information to navigate through the environment. For example, if the sensor(s) detect that the vehicle is approaching an obstacle, as determined by the computer-implemented controller, the controller adjusts the vehicle's directional controls to cause the vehicle to navigate around the obstacle.

One such sensor is a light detection and ranging (LIDAR) device. A LIDAR actively estimates distances to environmental features while scanning through a scene to assembly a cloud of point positions indicative of the three-dimensional shape of the environmental scene. Individual points are measured by generating a laser pulse and detecting a returning pulse, if any, reflected from an environmental object, and determining the distance to the reflective object according to the time delay between the emitted pulse and the reception of the reflected pulse. The laser, or set of lasers, can be rapidly and repeatedly scanned across a scene to provide continuous real-time information on distances to reflective objects in the scene. Combining the measured distances and the orientation of the laser(s) while measuring each distance allows for associating a three-dimensional position with each returning pulse. A three-dimensional map of points of reflective features is generated based on the returning pulses for the entire scanning zone. The three-dimensional point map thereby indicates positions of reflective objects in the scanned scene.

SUMMARY

A LIDAR device may transmit light pulses originating from one or more light sources and may receive reflected light pulses that are detected by one or more detectors. The LIDAR device may include a lens that both collimates the light from the one or more light sources and focuses the reflected light onto one or more detectors. Each light source may include a laser diode that emits an uncollimated laser beam that diverges more in a first direction than in a second direction and a cylindrical lens that pre-collimates the uncollimated laser beam in the first direction to provide a partially collimated laser beam.

In a first aspect, example embodiments provide a LIDAR device that includes at least one laser diode, at least one cylindrical lens, at least one detector, and an objective lens. The at least one laser diode is configured to emit an uncollimated laser beam that includes light in a narrow wavelength range. The uncollimated laser beam has a first divergence in a first direction and a second divergence in a second direction. The first divergence is greater than the second divergence. The at least one cylindrical lens is configured to pre-collimate the uncollimated laser beam in the first direction to provide a partially collimated laser beam that has a third divergence in the first direction and a fourth divergence in the second direction. The third divergence is less than the fourth divergence,

and the fourth divergence is substantially equal to the second divergence. The at least one detector is configured to detect light having wavelengths in the narrow wavelength range. The objective lens is configured to (i) collimate the partially collimated laser beam to provide a collimated laser beam for transmission into an environment of the LIDAR device and (ii) focus object-reflected light onto the at least one detector. The object-reflected light includes light from the collimated laser beam that has reflected from one or more objects in the environment of the LIDAR device.

In a second aspect, example embodiments provide a LIDAR device that includes a plurality of light sources, in which each light source is configured to emit partially collimated light, a plurality of detectors, in which each detector is associated with a respective light source in the plurality of light sources, a lens, and a mirror. The lens is configured to (i) collimate the partially collimated light from the light sources to provide collimated light for transmission into an environment of the LIDAR device and (ii) focus onto each detector any object-reflected light from the detector's associated light source that has reflected from one or more objects in the environment of the LIDAR device. The mirror is configured to rotate about an axis and, while rotating, reflect the collimated light from the lens into the environment and reflect any object-reflected light from the environment into the lens.

In a third aspect, example embodiments provide a method. The method involves emitting an uncollimated laser beam from a laser diode. The uncollimated laser beam has a first divergence in a first direction and a second divergence in a second direction. The first divergence is greater than the second divergence. The method further involves pre-collimating the laser beam in the first direction to provide a partially collimated laser beam. The partially collimated laser beam has a third divergence in the first direction and a fourth divergence in the second direction. The third divergence is less than the fourth divergence, and the fourth divergence is substantially equal to the second divergence. The method also involves collimating, by a lens, the partially collimated laser beam to provide a collimated laser beam and transmitting the collimated laser beam into an environment. In addition, the method involves collecting object-reflected light and focusing, by the lens, the object-reflected light through a focusing path onto a detector. The object-reflected light includes light from the collimated laser beam that has reflected from one or more objects in the environment.

In a fourth aspect, exemplary embodiments provide a LIDAR device that includes means for transmitting an uncollimating laser beam that has a first divergence in a first direction and a second divergence in a second direction, in which the first divergence is greater than the second divergence. The LIDAR device further includes means for pre-collimating the uncollimated laser beam in the first direction to provide a partially collimated laser beam that has a third divergence in the first direction and a fourth divergence in the second direction, in which he third divergence is less than the fourth divergence and the fourth divergence is substantially equal to the second divergence. In addition, the LIDAR device includes means for collimating the partially collimated laser beam, means for transmitting the partially collimated laser beam into an environment of the LIDAR device, means for collecting object-reflected light that includes light from the collimated laser beam that has reflected from one or more objects in the environment, and means for focusing the object-reflected light onto a detector.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1**A is a top schematic view of a LIDAR device, in accordance with an example embodiment.

FIG. **1**B is a side schematic view of a portion of the LIDAR device of FIG. **1**A, in accordance with an example embodiment.

FIG. **1**C is a front schematic view of a portion of the LIDAR device of FIG. **1**A, in accordance with an example embodiment.

FIG. **2**A is a view of a laser diode, in accordance with an example embodiment.

FIG. **2**B is a view of the laser diode of FIG. **2**A in combination with a cylindrical lens, in accordance with an example embodiment.

FIG. **2**C is another view of the laser diode and cylindrical lens combination of FIG. **2**B, in accordance with an example embodiment.

FIG. **3** is schematic diagram of the LIDAR device of FIG. **1**A transmitting a collimated laser beam, in accordance with an example embodiment.

FIG. **4** is a view of an aperture of a lens in the LIDAR device of FIG. **1**A, in accordance with an example embodiment.

FIG. **5**A illustrates a scenario in which LIDAR device scanning an environment that includes two objects, in accordance with an example embodiment.

FIG. **5**B illustrates a point cloud for the two objects scanned in the scenario illustrated in FIG. **5**A, in accordance with an example embodiment.

FIG. **6** is a flow chart of a method, in accordance with an example embodiment.

DETAILED DESCRIPTION

A LIDAR device may transmit light pulses originating from one or more light sources and may receive reflected light pulses that are detected by one or more detectors. The LIDAR device may include a transmit/receive lens that both collimates the light from the one or more light sources and focuses the reflected light onto the one or more detectors. By using a transmit/receive lens that performs both of these functions, instead of a transmit lens for collimating and a receive lens for focusing, advantages with respect to size, cost, and/or complexity can be provided.

Each light source may include a respective laser diode and cylindrical lens. The laser diode may emit an uncollimated laser beam that diverges more in a first direction than in a second direction. The cylindrical lens may pre-collimate the uncollimated laser beam in the first direction to provide a partially collimated laser beam, thereby reducing the divergence in the first direction. In some examples, the partially collimated laser beam diverges less in the first direction than in the second direction. The transmit/receive lens receives the partially collimated laser beams from the one or more light sources via a transmission path and collimates the partially collimated laser beams to provide collimated laser beams that are transmitted into an environment of the LIDAR device.

The collimated light transmitted from the LIDAR device into the environment may reflect from one or more objects in the environment to provide object-reflected light. The transmit/receive lens may collect the object-reflected light and focus the object-reflected light through a focusing path onto the one or more detectors. The transmission path through which the transmit/receive lens receives the light from the light sources may include a reflective element, such as a plane mirror or prism, that partially obstructs the focusing path. However, by providing partially collimated laser beams that diverge primarily in one direction, the beam widths of the partially collimated laser beams can be made relatively small in comparison to the aperture of the transmit/receive lens, as can the dimensions of the reflective element that accommodates the beam widths of the partially collimated laser beams.

FIGS. **1**A, **1**B, and **1**C illustrate an example LIDAR device **100**. In this example, LIDAR device **100** includes light sources **102**, **104**, and **106** and detectors **108**, **110**, and **112**. Each of light sources **102**, **104**, and **106** emits light in a wavelength range that can be detected by detectors **108**, **110**, and **112**. The wavelength range could, for example, be in the ultraviolet, visible, and/or infrared portions of the electromagnetic spectrum. In some examples, the wavelength range is a narrow wavelength range, such as provided by lasers. In addition, the light emitted by light sources **102**, **104**, and **106** could be in the form of pulses.

The light that is emitted by light sources **102**, **104**, and **106** is collimated by a lens **114**. The collimated light is then transmitted into an environment of LIDAR device **100** via a mirror **116**. The light transmitted from LIDAR device **100** could be reflected by one or more objects in the environment. The light reflected from such objects may reach mirror **116** and be reflected into lens **114**. Lens **114** may then focus the object-reflected light onto one or more of detectors **108**, **110**, and **112**.

Within LIDAR device **100**, light sources **102**, **104**, and **106** could be located in a different area than detectors **108**, **110**, and **112**. As shown in FIG. **1**B, detectors **108**, **110**, and **112** are arranged vertically in a focal plane **120** of lens **114**. As shown in FIG. **1**C, light sources **102**, **104**, and **106** are arranged vertically in a separately-located focal plane **122** of lens **114**. Thus, as a top view of LIDAR device **100**, FIG. **1**A shows light source **102** as the top-most light source in focal plane **122** and shows detector **108** as the top-most detector in focal plane **120**.

To reach lens **114**, the light emitted from light sources **102**, **104**, and **106** may travel through a transmission path defined by one or more reflective elements, such as a plane mirror **124**. In addition, light sources **102**, **104**, and **106** can be arranged to emit light in different directions. As shown in FIG. **1**C, light sources **102**, **104**, and **106** emit light toward plane mirror **124** in directions indicated by rays **132*a***, **134*a***, and **136*a***, respectively. As shown in FIG. **1**B, rays **132*a***, **134*a***, and **136*a***, are reflected by plane mirror **124**, as rays **132*b***, **134*b***, and **136*b***, respectively. Rays **132*b***, **134*b***, and **136*b*** then pass through lens **114** and are reflected by mirror **116**. FIG. **1**A shows that ray **132*b*** is reflected by mirror **116** as ray **132*c***. Rays **134*b*** and **136*b*** may be similarly reflected by mirror **116** but in different vertical directions. In this regard, the vertical arrangement of light sources **102**, **104**, and **106**, results in rays **132*b***, **134*b***, and **136*b*** being incident upon mirror **116** at different vertical angles, so that mirror **116** reflects the light from light sources **102**, **104**, and **106** in different vertical directions.

Light from one or more of light sources **102**, **104**, and **106** transmitted by LIDAR device **100** via mirror **116** can be reflected back toward mirror **116** from one of more objects in the environment of LIDAR device **100** as object-reflected light. Mirror **116** can then reflect the object-reflected light into lens **114**. As shown in FIG. **1**B, lens **114** can focus the object-reflected light onto one or more of detectors **108**, **110**, and **112**, via respective focusing paths **138**, **140**, and **142**, depending on the angle at which lens **114** receives the object-reflected light.

The angle of the object-reflected light received by lens **114** may depend on which of light sources **102**, **104**, and **106** was

the source of the object-reflected light. For example, lens **114** may focus object-reflected light originating from light source **102** onto detector **108** via focusing path **138**, may focus object-reflected light originating from light source **104** onto detector **110** via focusing path **140**, and may focus object-reflected light originating from light source **106** onto detector **112** via focusing path **142**. In this way, LIDAR device **100** may define separate transmit/receive channels, such that light transmitted by a particular light source is received and detected by a particular detector.

Given the function of lens **114** of focusing object-reflected light onto one or more detectors, lens **114** could be described as an objective lens of LIDAR device **100**. Further, lens **114** could have any shape that enables it to perform this focusing function. In some examples, lens **114** is an aspherical lens. The shape and focal length of the aspherical lens could be optimized for the wavelengths of light emitted by light sources **102**, **104**, and **106**. For example, light sources **102**, **104**, and **106** could emit light with a wavelength of about 905 nm, and lens **114** could be an aspherical lens with a focal length of about 100 mm. Alternatively, lens **114** could be a spherical lens, such as a plano-convex lens or a biconvex lens.

As shown, plane mirror **124** partially obstructs focusing paths **138**, **140**, and **142**, through which lens **114** focuses light onto detectors **108**, **110**, and **112**. However, the amount of light loss caused by this obstruction can be made acceptably small by making the dimensions of plane mirror **124** small relative to the aperture of lens **114**. As described in more detail below, plane mirror **124** can be made small in at least one dimension by partially collimating the light emitted by light sources **102**, **104**, and **106**.

As described above, the light transmitted by LIDAR device **100** may be transmitted in a range of vertical directions, based on the vertical arrangement of light sources **102**, **104**, and **106** in focal plane **122**. Alternatively or additionally, the light sources could have a horizontal arrangement in focal plane **122**, so that the light transmitted by LIDAR device **100** is transmitted in a range of horizontal directions. Thus, while FIGS. **1**A, **1**B, and **1**C show three light sources arranged vertically in focal plane **122**, LIDAR device **100** could include a greater or fewer number of light sources, which light sources could be arranged horizontally and/or vertically in focal plane **122**.

FIG. **1**B also shows three detectors arranged vertically in focal plane **120**. However, LIDAR device **100** could include a greater or fewer number of detectors, which detectors could be arranged horizontally and/or vertically in focal plane **120**. As described above, each particular detector in LIDAR device **100** could be associated with a particular light source, such that light from that particular light source that is transmitted from LIDAR device **100** and then reflected by an object in the environment is focused by lens **114** onto that particular detector. These associations between light sources and detectors may define transmit/receive channels. Thus, in the example shown in FIGS. **1**A, **1**B and **1**C, LIDAR device **100** has a first transmit/receive channel in which detector **108** is associated with light source **102**, a second transmit/receive channel in which detector **110** is associated with light source **104**, and a third transmit/receive channel in which detector **112** is associated with light source **106**. In other examples, a LIDAR device could have a greater or fewer number of transmit/receive channels.

The use of multiple light sources and multiple detectors can allow LIDAR device **100** to interrogate multiple portions of its environment simultaneously or substantially simultaneously. For example, light sources **102**, **104**, and **106** could emit light pulses either simultaneously or in rapid succession according to a firing cycle.

The vertical arrangement of light sources **102**, **104**, and **106** enables LIDAR device **100** to transmit in multiple vertical directions, as described above. By moving mirror **116**, LIDAR device **100** can also transmit in a range of horizontal directions. As shown, mirror **116** has three reflective surfaces **150**, **152**, and **154**, and mirror **116** rotates about a vertical axis **156**, as indicated by the curved arrow. In the configuration shown in FIG. **1**A, ray **132***b* is incident on reflective surface **150** and is reflected as ray **132***c*. Rays **134***b* and **136***b* shown in FIG. **1**B are similarly incident on reflective surface **150**, resulting in respective reflective rays. As mirror **116** rotates, the angles of incidence of rays **132***b*, **134***b*, and **136***b* will change, which causes the directions of the reflected rays to change. In this way, the rotation of mirror **116** about vertical axis **156** can deflect the light from each of the light sources through a range of angles in the horizontal plane. Mirror **116** can also deflect the light from the light sources vertically. For example, reflective surfaces **150**, **152**, and **154** may each have a different tilt with respect to vertical axis **156**.

Although FIG. **1**A shows mirror **116** with three reflective surfaces, it is to be understood that mirror **116** could have a greater or fewer number of reflective surfaces. In addition, while mirror **116** has been described as rotating about vertical axis **156**, mirror **116** could rotate about a horizontal axis or an axis in some other direction. In addition, instead of rotating, mirror **116** could oscillate through a range of angles. For example, mirror **116** could have a single reflective surface that wobbles back and forth about an axis without making a complete rotation.

In some examples, mirror **116** could be omitted. In order to transmit and receive through a range of horizontal directions, an optical assembly including light sources **102-106**, detectors **108-112**, lens **114**, and mirror **124** could rotate together about a vertical axis. The optical assembly could spin about the vertical axis in a particular direction, or the optical assembly could oscillate back and forth though a range of angles about the vertical axis. The range of angles could be, for example, 180 degrees, 120 degrees, 60 degrees, 30 degrees, or any other range of angles that is less than a full rotation.

As noted above, the light from light sources **102**, **104**, and **106** could be partially collimated. FIGS. **2**A, **2**B, and **2**C illustrate an example of how such partial collimation could be achieved. In this example, a light source **200** is made up of a laser diode **202** and a cylindrical lens **204**. As shown in FIG. **2**A, laser diode **202** has an aperture **206** with a shorter dimension corresponding to a fast axis **208** and a longer dimension corresponding to a slow axis **210**. FIGS. **2**B and **2**C show an uncollimated laser beam **212** being emitted from laser diode **202**. Laser beam **212** diverges in two directions, one direction defined by fast axis **208** and another, generally orthogonal direction defined slow axis **210**. FIG. **2**B shows the divergence of laser beam **212** along fast axis **208**, whereas FIG. **2**C shows the divergence of laser beam **212** along slow axis **210**. Laser beam **212** diverges more quickly along fast axis **208** than along slow axis **210**.

In one specific example, laser diode **202** is an Osram SPL DL90_3 nanostack pulsed laser diode that emits pulses of light with a range of wavelengths from about 896 nm to about 910 nm (a nominal wavelength of 905 nm). In this specific example, the aperture has a shorter dimension of about 10 microns, corresponding to its fast axis, and a longer dimension of about 200 microns, corresponding to its slow axis. The divergence of the laser beam in this specific example is about 25 degrees along the fast axis and about 11 degrees along the

slow axis. When this type of laser diode is used in light sources **102**, **104**, and **106**, lens **114** could be an aspherical lens with a focal length of about 100 mm. It is to be understood that this specific example is illustrative only. Laser diode **202** could have a different configuration, different aperture sizes, different beam divergences, and/or emit different wavelengths.

As shown in FIGS. **2**B and **2**C, cylindrical lens **204** may be positioned in front of aperture **206** with its cylinder axis **214** generally parallel to slow axis **210** and perpendicular to fast axis **208**. In this arrangement, cylindrical lens **204** can pre-collimate laser beam **212** along fast axis **208**, resulting in partially collimated laser beam **216**. In some examples, this pre-collimation may reduce the divergence along fast axis **208** to about one degree or less. Nonetheless, laser beam **216** is only partially collimated because the divergence along slow axis **210** may be largely unchanged by cylindrical lens **204**. Thus, whereas uncollimated laser beam **212** emitted by laser diode has a higher divergence along fast axis **208** than along slow axis **210**, partially collimated laser beam **216** provided by cylindrical lens **204** may have a higher divergence along slow axis **210** than along fast axis **208**. Further, the divergences along slow axis **210** in uncollimated laser beam **212** and in partially collimated laser beam **216** may be substantially equal.

In one example, cylindrical lens **204** is a microrod lens with a diameter of about 600 microns that is placed about 250 microns in front of aperture **206**. The material of the microrod lens could be, for example, fused silica or a borosilicate crown glass, such as Schott BK7. Cylindrical lens **204** could also be used to provide magnification along fast axis **208**. For example, if the dimensions of aperture **206** are 10 microns by 200 microns, as previously described, and cylindrical lens **204** is a microrod lens as described above, then cylindrical lens **204** may magnify the shorter dimension (corresponding to fast axis **208**) by about 20 times. This magnification effectively stretches out the shorter dimension of aperture **206** to about the same as the longer dimension. As a result, when light from laser beam **216** is focused, for example, focused onto a detector, the focused spot could have a substantially square shape instead of the rectangular slit shape of aperture **206**.

FIG. **3** illustrates a scenario in which light sources **102**, **104**, and **106** in LIDAR device **100** are each made up of a respective laser diode and cylindrical lens, for example, as shown in FIGS. **2**A-**2**C. As shown, light source **102** emits a partially collimated laser beam **350** that is reflected by plane mirror **124** into lens **114**. In this example, partially collimated laser beam **350** has less divergence in the horizontal plane (the drawing plane of FIG. **3**) than in the vertical plane. Thus, the laser diode in light source **102** may be oriented with its fast axis in the horizontal plane and its slow axis in the vertical plane. For purposes of illustration, partially collimated laser beam **350** is shown in FIG. **3** with no divergence in horizontal plane. It is to be understood, however, that some amount of divergence is possible.

Lens **114** collimates partially collimated laser beam **350** to provide collimated laser beam **352** that is reflected by mirror **116** into the environment of LIDAR device **100**. Light from collimated laser beam **352** may be reflected by one or more objects in the environment of LIDAR device **100**. The object-reflected light may reach mirror **116** and be reflected into lens **114**. Lens **114**, in turn, focuses the object-reflected light through focusing path **138** onto detector **108**. Although FIG. **3** shows a partially collimated laser beam from only light source **102**, it is to be understood that light sources **104** and **106** could also emit partially collimated laser beams that are collimated by lens **114** to provide collimated laser beams that are transmitted from LIDAR device **100** via mirror **116**. Thus, object-reflected light from the collimated laser beams originating from one or more of light sources **102**, **104**, and **106** may reach mirror **116** and be reflected into lens **114**, which focuses the object-reflected light onto one or more of detectors **108**, **110**, and **112**, respectively.

As shown in FIG. **3**, the transmission path through which partially collimated laser beam **350** reaches lens **114** includes a plane mirror **124** that partially obstructs focusing path **138**. However, the obstruction created by plane mirror **124** can be minimized by having the dimensions of plane **124** correspond to the dimensions of partially collimated laser beam **350** incident upon it. As shown, partially collimated laser beam **350** has a beam width **354** in the horizontal plane. Partially collimated laser beam **350** also has a beam width in the vertical plane (not shown), which could be substantially larger than beam width **354** due to the greater divergence in the vertical plane. To minimize obstruction of focusing path **138**, plane mirror **124** could have horizontal and vertical dimensions that are just large enough to accommodate the horizontal and vertical beam widths of partially collimated laser beam **350**, as well as the horizontal and vertical beam widths of the partially collimated laser beams emitted by light sources **104** and **106**. As a result, plane mirror **124** could have a larger cross-section in the vertical plane than in the horizontal plane.

To illustrate how the dimensions of plane mirror **124** may compare to the dimensions of lens **114** in order to minimize the obstruction of focusing path **138**, FIG. **4**, shows a view from mirror **116** of lens **114** and plane mirror **124** behind it. For purposes of illustration, lens **114** is shown with a generally rectangular aperture having a horizontal dimension **400** and a vertical dimension **402**. Of course, other aperture shapes are possible as well. In this example, plane mirror **124** has a vertical dimension **404** that is the same or similar to vertical dimension **402** of lens **114**, but plane mirror **124** has a horizontal dimension **406** that is much smaller than the horizontal dimension **400** of lens **114**. By having horizontal dimension **406** of plane mirror **124** be only a fraction of horizontal dimension **400** of horizontal dimension **400** of lens **114**, plane mirror **124** may obstruct only a fraction of the aperture of lens **114**.

FIGS. **5**A and **5**B illustrate an example application of a LIDAR device **500**, which could have the same or similar configuration as LIDAR device **100** shown in FIG. **1**. In this example application, LIDAR device **500** is used to scan an environment that includes a road. Thus, LIDAR device **500** could be in a vehicle, such as an autonomous vehicle, that is traveling on the road. The environment of LIDAR device **500** in this example includes another vehicle **502** and a road sign **504**. To scan through the environment, LIDAR device **500** rotates a scanning element, which could be the same or similar to mirror **116**, according to motion reference arrow **506** with angular velocity w. While rotating, LIDAR device **500** regularly (e.g., periodically) emits pulsed laser beams, such as laser beam **508**. Light from the emitted laser beams is reflected by objects in the environment, such as vehicle **502** and sign **504**, and are detected by one or more detectors in LIDAR device **500**. Precisely time-stamping the receipt of the reflected signals allows for associating each reflected signal (if any is received at all) with the most recently emitted laser pulse and measuring the time delay between emission of the laser pulse and reception of the reflected light. The time delay provides an estimate of the distance to the reflective feature based on the speed of light in the intervening atmosphere. Combining the distance information for each reflected signal

with the orientation of scanning element in LIDAR device **500** for the respective pulse emission allows for determining a position of the reflective feature in three-dimensions.

FIG. **5**B symbolically illustrates a point cloud resulting from LIDAR device **500** scanning the environment shown in FIG. **5**A. For purposes of illustration, the scan is assumed to be in an x-y plane that is generally horizontal (e.g., parallel to the surface of the road). It is to be understood, however, that the scan could include a vertical component (z-dimension) as well. In this example, the point cloud includes spatial points **512** corresponding to reflections from vehicle **502** and spatial points **514** corresponding to reflections from sign **504**. Each spatial point in the point cloud has a line of sight ("LOS") distance from LIDAR device **500** and an azimuthal angle ϕ in the x-y plane. In this way, the scanning by LIDAR **500** can provide information regarding the locations of reflective objects in its environment.

FIG. **6** is a flow chart of an example method **600** of operating a LIDAR device, such as LIDAR device **100**. Method **600** involves emitting an uncollimated laser beam from a laser diode, in which the laser beam has a first divergence in a first direction and a second divergence in a second direction, with the first divergence being greater than the second divergence (block **602**). The laser diode could be configured as shown in FIGS. **2**A-**2**C with a fast axis and a slow axis. Thus, the first direction could correspond to the fast axis and the second direction could correspond to the slow axis.

Method **600** further involves pre-collimating the uncollimated laser beam in the first direction to provide a partially collimated laser beam that has a third divergence in the first direction and a fourth divergence in the second direction, with the third divergence being less than the fourth divergence and the fourth divergence being substantially equal to the second divergence (block **604**). The pre-collimation could be achieved by transmitting the laser beam through a cylindrical lens, as shown in FIGS. **2**B and **2**C and described above. Thus, the cylindrical lens could reduce the divergence along the fast axis so that it becomes less than the divergence along the slow axis, while keeping the divergence along the slow axis substantially the same.

A lens, such as lens **114** shown in FIGS. **1**A and **1**B, collimates the partially collimated laser beam to provide a collimated laser beam (block **606**). The lens could be an aspherical lens or a spherical lens. The collimated laser beam is then transmitted into an environment (block **608**). Transmitting the collimating laser beam into the environment could involve a rotating mirror, such as mirror **116**, reflecting the collimated laser beam from the lens into the environment.

Method **600** also involves collecting object-reflected light, in which the object-reflected light includes light from the collimated laser beam that has reflected from one or more objects in the environment (block **610**). Collecting the object-reflected light could involve a rotating mirror, such as mirror **116**, reflecting the object-reflected light from the environment into the lens used to collimate the laser beam. The lens may also focus the object-reflected light through a focusing path onto a detector (block **612**). In some examples, the lens may receive the partially collimated laser beam via a reflective element, such as a plane mirror or prism, that partially obstructs the focusing path. However, as discussed above, the obstruction can be minimized by having the dimensions of the reflective element match the dimensions of the partially collimated laser beam.

Although method **600** has been described with respect to one laser diode, it is to be understood that multiple laser diodes could be used, each emitting a respective laser beam that is transmitted into the environment as a collimated laser beam. The collimated laser beams could be transmitted simultaneously or sequentially. Further, the collimated laser beam could be transmitted in different direction. The object-reflected light that is collected could include light from any of the transmitted collimated laser beams.

While various example aspects and example embodiments have been disclosed herein, other aspects and embodiments will be apparent to those skilled in the art. The various example aspects and example embodiments disclosed herein are for purposes of illustration and are not intended to be limiting, with the true scope and spirit being indicated by the following claims.

What is claimed is:

1. A light detection and ranging (LIDAR) device, comprising:

at least one laser diode, wherein the at least one laser diode is configured to emit an uncollimated laser beam comprising light in a narrow wavelength range, wherein the uncollimated laser beam has a first divergence in a first direction and a second divergence in a second direction, and wherein the first divergence is greater than the second divergence;

at least one cylindrical lens, wherein the at least one cylindrical lens is configured to pre-collimate the uncollimated laser beam in the first direction to provide a partially collimated laser beam that has a third divergence in the first direction and a fourth divergence in the second direction, wherein the third divergence is less than the fourth divergence and the fourth divergence is substantially equal to the second divergence;

at least one detector, wherein the at least one detector is configured to detect light having wavelengths in the narrow wavelength range; and

an objective lens, wherein the objective lens is configured to (i) collimate the partially collimated laser beam to provide a collimated laser beam for transmission into an environment of the LIDAR device and (ii) focus object-reflected light onto the at least one detector, wherein the object-reflected light comprises light from the collimated laser beam that has reflected from one or more objects in the environment of the LIDAR device.

2. The LIDAR device of claim **1**, wherein the objective lens receives the partially collimated laser beam via a transmission path and focuses the object-reflected light through a focusing path, and wherein the transmission path includes a reflective element that partially obstructs the focusing path.

3. The LIDAR device of claim **2**, wherein the reflective element comprises a plane mirror.

4. The LIDAR device of claim **1**, wherein the at least one laser diode comprises a plurality of laser diodes, the at least one detector comprises a plurality of detectors, and the at least one cylindrical lens comprises a plurality of cylindrical lenses, such that each cylindrical lens in the plurality of cylindrical lenses is associated with a corresponding laser diode in the plurality of laser diodes.

5. The LIDAR device of claim **4**, wherein each laser diode is configured to emit a respective uncollimated laser beam in a respective direction, and wherein each cylindrical lens is configured to pre-collimate the uncollimated laser beam produced by its corresponding laser diode to provide a corresponding partially collimated laser beam that is then collimated by the objective lens to provide a corresponding collimated laser beam.

6. The LIDAR device of claim **5**, wherein each detector in the plurality of detectors is associated with a corresponding laser diode in the plurality of laser diodes, and wherein the objective lens is configured to focus onto each detector a

respective portion of the object-reflected light that comprises light from the detector's corresponding laser diode.

7. The LIDAR device of claim **6**, wherein each laser diode has a rectangular aperture that has a short dimension and a long dimension, and wherein each cylindrical lens is configured to magnify the short dimension of the aperture of its corresponding laser diode such that the light from the laser diode that is focused onto the laser diode's corresponding detector has a substantially square shape.

8. The LIDAR device of claim **1**, wherein the at least one cylindrical lens comprises at least one microrod lens.

9. The LIDAR device of claim **1**, wherein the narrow wavelength range includes wavelengths of about 905 nanometers.

10. The LIDAR device of claim **1**, wherein the objective lens is an aspherical lens.

11. The LIDAR device of claim **1**, further comprising a mirror, wherein the mirror is configured to reflect the collimated laser beam from the objective lens into the environment and to reflect the object-reflected light from the environment into the objective lens.

12. The LIDAR device of claim **11**, wherein the mirror rotates about a vertical axis.

13. The LIDAR device of claim **12**, wherein the mirror comprises a plurality of reflective surfaces, each reflective surface having a different tilt with respect to the vertical axis.

14. A light detection and ranging (LIDAR) device, comprising:

a plurality of light sources, wherein each light source is configured to emit partially collimated light;

a plurality of detectors, wherein each detector in the plurality of detectors is associated with a respective light source in the plurality of light sources;

a first mirror, wherein the first mirror is configured to reflect the partially collimated light from the light sources;

a second mirror, wherein the second mirror is configured to rotate about an axis; and

a lens, wherein the lens is configured to (i) receive, via the first mirror, the partially collimated light from the light sources, (ii) collimate the partially collimated light from the light sources to provide collimated light, wherein the second mirror is configured to reflect the collimated light from the lens into an environment of the LIDAR device, and (iii) focus, via a focusing path, onto each detector any object-reflected light from the detector's associated light source that has reflected from one or more objects in the environment of the LIDAR device, wherein the second mirror is configured to reflect the object-reflected light from the environment into the lens,

wherein the first mirror partially obstructs the focusing path.

15. The LIDAR device of claim **14**, wherein each light source in the plurality of light sources comprises a respective laser diode and a respective cylindrical lens.

16. The LIDAR device of claim **14**, wherein the second mirror comprises a plurality of reflective surfaces, each reflective surface having a different tilt with respect to the axis.

17. A method comprising:

emitting an uncollimated laser beam from a laser diode, wherein the uncollimated laser beam has a first divergence in a first direction and a second divergence in a second direction, and wherein the first divergence is greater than the second divergence;

pre-collimating the uncollimated laser beam in the first direction to provide a partially collimated laser beam, wherein the partially collimated laser beam has a third divergence in the first direction and a fourth divergence in the second direction, and wherein the third divergence is less than the fourth divergence and the fourth divergence is substantially equal to the second divergence;

collimating, by a lens, the partially collimated laser beam to provide a collimated laser beam;

transmitting the collimated laser beam into an environment;

collecting object-reflected light, wherein the object-reflected light comprises light from the collimated laser beam that has reflected from one or more objects in the environment; and

focusing, by the lens, the object-reflected light through a focusing path onto a detector, wherein the lens receives the partially collimated laser beam via a plane mirror that partially obstructs the focusing path.

18. The method of claim **17**, wherein pre-collimating the uncollimated laser beam in the first direction to provide a partially collimated laser beam comprises transmitting the uncollimated laser beam through a cylindrical lens.

19. The method of claim **17**, wherein transmitting the collimated laser beam into an environment comprises a rotating mirror reflecting the collimated laser beam from the lens into the environment, and wherein collecting object-reflected light comprises the rotating mirror reflecting the object-reflected light from the environment into the lens.

20. The method of claim **17**, further comprising:

rotating an optical assembly about an axis while transmitting the collimated laser beam into the environment and collecting object-reflected light, wherein the optical assembly includes the laser diode, the lens, the detector, and the plane mirror.

* * * * *

JS-CAND 44 (Rev. 07/16)

CIVIL COVER SHEET

The JS-CAND 44 civil cover sheet and the information contained herein neither replace nor supplement the filing and service of pleadings or other papers as required by law, except as provided by local rules of court. This form, approved in its original form by the Judicial Conference of the United States in September 1974, is required for the Clerk of Court to initiate the civil docket sheet. *(SEE INSTRUCTIONS ON NEXT PAGE OF THIS FORM.)*

I. (a) PLAINTIFFS

Waymo LLC

(b) County of Residence of First Listed Plaintiff: San Francisco
(EXCEPT IN U.S. PLAINTIFF CASES)

(c) Attorneys *(Firm Name, Address, and Telephone Number)*

Charles K. Verhoeven
Quinn Emanuel Urquhart & Sullivan, LLP
50 California Street, 22nd Floor, San Francisco, 94111

DEFENDANTS

Uber Technologies, Inc., Ottomotto LLC, Otto Trucking LLC

County of Residence of First Listed Defendant: San Francisco
(IN U.S. PLAINTIFF CASES ONLY)

NOTE: IN LAND CONDEMNATION CASES, USE THE LOCATION OF THE TRACT OF LAND INVOLVED.

Attorneys *(If Known)*

II. BASIS OF JURISDICTION *(Place an "X" in One Box Only)*

- [ ] 1 U.S. Government Plaintiff
- [x] 3 Federal Question *(U.S. Government Not a Party)*
- [ ] 2 U.S. Government Defendant
- [ ] 4 Diversity *(Indicate Citizenship of Parties in Item III)*

III. CITIZENSHIP OF PRINCIPAL PARTIES *(Place an "X" in One Box for Plaintiff and One Box for Defendant)*

(For Diversity Cases Only)

	PTF	DEF		PTF	DEF
Citizen of This State	[ ] 1	[ ] 1	Incorporated *or* Principal Place of Business In This State	[ ] 4	[ ] 4
Citizen of Another State	[ ] 2	[ ] 2	Incorporated *and* Principal Place of Business In Another State	[ ] 5	[ ] 5
Citizen or Subject of a Foreign Country	[ ] 3	[ ] 3	Foreign Nation	[ ] 6	[ ] 6

IV. NATURE OF SUIT *(Place an "X" in One Box Only)*

CONTRACT
- [ ] 110 Insurance
- [ ] 120 Marine
- [ ] 130 Miller Act
- [ ] 140 Negotiable Instrument
- [ ] 150 Recovery of Overpayment Of Veteran's Benefits
- [ ] 151 Medicare Act
- [ ] 152 Recovery of Defaulted Student Loans (Excludes Veterans)
- [ ] 153 Recovery of Overpayment of Veteran's Benefits
- [ ] 160 Stockholders' Suits
- [ ] 190 Other Contract
- [ ] 195 Contract Product Liability
- [ ] 196 Franchise

REAL PROPERTY
- [ ] 210 Land Condemnation
- [ ] 220 Foreclosure
- [ ] 230 Rent Lease & Ejectment
- [ ] 240 Torts to Land
- [ ] 245 Tort Product Liability
- [ ] 290 All Other Real Property

TORTS

PERSONAL INJURY
- [ ] 310 Airplane
- [ ] 315 Airplane Product Liability
- [ ] 320 Assault, Libel & Slander
- [ ] 330 Federal Employers' Liability
- [ ] 340 Marine
- [ ] 345 Marine Product Liability
- [ ] 350 Motor Vehicle
- [ ] 355 Motor Vehicle Product Liability
- [ ] 360 Other Personal Injury
- [ ] 362 Personal Injury - Medical Malpractice

PERSONAL INJURY
- [ ] 365 Personal Injury – Product Liability
- [ ] 367 Health Care/ Pharmaceutical Personal Injury Product Liability
- [ ] 368 Asbestos Personal Injury Product Liability

PERSONAL PROPERTY
- [ ] 370 Other Fraud
- [ ] 371 Truth in Lending
- [ ] 380 Other Personal Property Damage
- [ ] 385 Property Damage Product Liability

CIVIL RIGHTS
- [ ] 440 Other Civil Rights
- [ ] 441 Voting
- [ ] 442 Employment
- [ ] 443 Housing/ Accommodations
- [ ] 445 Amer. w/Disabilities–Employment
- [ ] 446 Amer. w/Disabilities–Other
- [ ] 448 Education

PRISONER PETITIONS

Habeas Corpus:
- [ ] 463 Alien Detainee
- [ ] 510 Motions to Vacate Sentence
- [ ] 530 General
- [ ] 535 Death Penalty

Other:
- [ ] 540 Mandamus & Other
- [ ] 550 Civil Rights
- [ ] 555 Prison Condition
- [ ] 560 Civil Detainee– Conditions of Confinement

FORFEITURE/PENALTY
- [ ] 625 Drug Related Seizure of Property 21 USC § 881
- [ ] 690 Other

LABOR
- [ ] 710 Fair Labor Standards Act
- [ ] 720 Labor/Management Relations
- [ ] 740 Railway Labor Act
- [ ] 751 Family and Medical Leave Act
- [ ] 790 Other Labor Litigation
- [ ] 791 Employee Retirement Income Security Act

IMMIGRATION
- [ ] 462 Naturalization Application
- [ ] 465 Other Immigration Actions

BANKRUPTCY
- [ ] 422 Appeal 28 USC § 158
- [ ] 423 Withdrawal 28 USC § 157

PROPERTY RIGHTS
- [ ] 820 Copyrights
- [x] 830 Patent
- [ ] 840 Trademark

SOCIAL SECURITY
- [ ] 861 HIA (1395ff)
- [ ] 862 Black Lung (923)
- [ ] 863 DIWC/DIWW (405(g))
- [ ] 864 SSID Title XVI
- [ ] 865 RSI (405(g))

FEDERAL TAX SUITS
- [ ] 870 Taxes (U.S. Plaintiff or Defendant)
- [ ] 871 IRS–Third Party 26 USC § 7609

OTHER STATUTES
- [ ] 375 False Claims Act
- [ ] 376 Qui Tam (31 USC § 3729(a))
- [ ] 400 State Reapportionment
- [ ] 410 Antitrust
- [ ] 430 Banks and Banking
- [ ] 450 Commerce
- [ ] 460 Deportation
- [ ] 470 Racketeer Influenced and Corrupt Organizations
- [ ] 480 Consumer Credit
- [ ] 490 Cable/Sat TV
- [ ] 850 Securities/Commodities/ Exchange
- [ ] 890 Other Statutory Actions
- [ ] 891 Agricultural Acts
- [ ] 893 Environmental Matters
- [ ] 895 Freedom of Information Act
- [ ] 896 Arbitration
- [ ] 899 Administrative Procedure Act/Review or Appeal of Agency Decision
- [ ] 950 Constitutionality of State Statutes

V. ORIGIN *(Place an "X" in One Box Only)*

- [x] 1 Original Proceeding
- [ ] 2 Removed from State Court
- [ ] 3 Remanded from Appellate Court
- [ ] 4 Reinstated or Reopened
- [ ] 5 Transferred from Another District *(specify)*
- [ ] 6 Multidistrict Litigation–Transfer
- [ ] 8 Multidistrict Litigation–Direct File

VI. CAUSE OF ACTION

Cite the U.S. Civil Statute under which you are filing ***(Do not cite jurisdictional statutes unless diversity)***:
35 U.S. Code § 271; 18 U.S. Code § 1836; Cal. Civ. Code § 3426; California Bus. & Prof. Code § 17200

Brief description of cause:
Trade Secret Misappropriation; Patent Infringement; Violation of California Bus. & Prof. Code § 17200

VII. REQUESTED IN COMPLAINT:

- [ ] CHECK IF THIS IS A CLASS ACTION UNDER RULE 23, Fed. R. Civ. P.

DEMAND $

CHECK YES only if demanded in complaint:
JURY DEMAND: [x] Yes [ ] No

VIII. RELATED CASE(S), IF ANY *(See instructions)*:

JUDGE

DOCKET NUMBER

IX. DIVISIONAL ASSIGNMENT (Civil Local Rule 3-2)

(Place an "X" in One Box Only) [ ] **SAN FRANCISCO/OAKLAND** [ ] **SAN JOSE** [ ] **EUREKA-MCKINLEYVILLE**

DATE: February 23, 2017 **SIGNATURE OF ATTORNEY OF RECORD:**

JS-CAND 44 (rev. 07/16)

INSTRUCTIONS FOR ATTORNEYS COMPLETING CIVIL COVER SHEET FORM JS-CAND 44

Authority For Civil Cover Sheet. The JS-CAND 44 civil cover sheet and the information contained herein neither replaces nor supplements the filings and service of pleading or other papers as required by law, except as provided by local rules of court. This form, approved in its original form by the Judicial Conference of the United States in September 1974, is required for the Clerk of Court to initiate the civil docket sheet. Consequently, a civil cover sheet is submitted to the Clerk of Court for each civil complaint filed. The attorney filing a case should complete the form as follows:

I. a) Plaintiffs-Defendants. Enter names (last, first, middle initial) of plaintiff and defendant. If the plaintiff or defendant is a government agency, use only the full name or standard abbreviations. If the plaintiff or defendant is an official within a government agency, identify first the agency and then the official, giving both name and title.

b) County of Residence. For each civil case filed, except U.S. plaintiff cases, enter the name of the county where the first listed plaintiff resides at the time of filing. In U.S. plaintiff cases, enter the name of the county in which the first listed defendant resides at the time of filing. (NOTE: In land condemnation cases, the county of residence of the "defendant" is the location of the tract of land involved.)

c) Attorneys. Enter the firm name, address, telephone number, and attorney of record. If there are several attorneys, list them on an attachment, noting in this section "(see attachment)."

II. Jurisdiction. The basis of jurisdiction is set forth under Federal Rule of Civil Procedure 8(a), which requires that jurisdictions be shown in pleadings. Place an "X" in one of the boxes. If there is more than one basis of jurisdiction, precedence is given in the order shown below.

(1) United States plaintiff. Jurisdiction based on 28 USC §§ 1345 and 1348. Suits by agencies and officers of the United States are included here.

(2) United States defendant. When the plaintiff is suing the United States, its officers or agencies, place an "X" in this box.

(3) Federal question. This refers to suits under 28 USC § 1331, where jurisdiction arises under the Constitution of the United States, an amendment to the Constitution, an act of Congress or a treaty of the United States. In cases where the U.S. is a party, the U.S. plaintiff or defendant code takes precedence, and box 1 or 2 should be marked.

(4) Diversity of citizenship. This refers to suits under 28 USC § 1332, where parties are citizens of different states. When Box 4 is checked, the citizenship of the different parties must be checked. (See Section III below; **NOTE: federal question actions take precedence over diversity cases.)**

III. Residence (citizenship) of Principal Parties. This section of the JS-CAND 44 is to be completed if diversity of citizenship was indicated above. Mark this section for each principal party.

IV. Nature of Suit. Place an "X" in the appropriate box. If the nature of suit cannot be determined, be sure the cause of action, in Section VI below, is sufficient to enable the deputy clerk or the statistical clerk(s) in the Administrative Office to determine the nature of suit. If the cause fits more than one nature of suit, select the most definitive.

V. Origin. Place an "X" in one of the six boxes.

(1) Original Proceedings. Cases originating in the United States district courts.

(2) Removed from State Court. Proceedings initiated in state courts may be removed to the district courts under Title 28 USC § 1441. When the petition for removal is granted, check this box.

(3) Remanded from Appellate Court. Check this box for cases remanded to the district court for further action. Use the date of remand as the filing date.

(4) Reinstated or Reopened. Check this box for cases reinstated or reopened in the district court. Use the reopening date as the filing date.

(5) Transferred from Another District. For cases transferred under Title 28 USC § 1404(a). Do not use this for within district transfers or multidistrict litigation transfers.

(6) Multidistrict Litigation Transfer. Check this box when a multidistrict case is transferred into the district under authority of Title 28 USC § 1407. When this box is checked, do not check (5) above.

(8) Multidistrict Litigation Direct File. Check this box when a multidistrict litigation case is filed in the same district as the Master MDL docket.

Please note that there is no Origin Code 7. Origin Code 7 was used for historical records and is no longer relevant due to changes in statute.

VI. Cause of Action. Report the civil statute directly related to the cause of action and give a brief description of the cause. **Do not cite jurisdictional statutes unless diversity.** Example: U.S. Civil Statute: 47 USC § 553. Brief Description: Unauthorized reception of cable service.

VII. Requested in Complaint. Class Action. Place an "X" in this box if you are filing a class action under Federal Rule of Civil Procedure 23.

Demand. In this space enter the actual dollar amount being demanded or indicate other demand, such as a preliminary injunction.

Jury Demand. Check the appropriate box to indicate whether or not a jury is being demanded.

VIII. Related Cases. This section of the JS-CAND 44 is used to identify related pending cases, if any. If there are related pending cases, insert the docket numbers and the corresponding judge names for such cases.

IX. Divisional Assignment. If the Nature of Suit is under Property Rights or Prisoner Petitions or the matter is a Securities Class Action, leave this section blank. For all other cases, identify the divisional venue according to Civil Local Rule 3-2: "the county in which a substantial part of the events or omissions which give rise to the claim occurred or in which a substantial part of the property that is the subject of the action is situated."

Date and Attorney Signature. Date and sign the civil cover sheet.